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LIST OF ABBREVIATIONS

Median Scenarios

M_NB_Nar:	median 50 feet or narrower and no median barrier
M_NB_Wide:	median wider than 50 feet and no median barrier
M_BW:	median concrete barrier placed in the center of a narrow median
M_GR:	median guardrail placed in the center of a median or at the nearside edge
M_CB_Near:	median cable barrier (near-side) with a lateral clearance 30 feet or less to the travelled way
M_CB_Far:	median cable barrier (far-side) with a lateral clearance more than 30 feet to the travelled way

Roadside Scenarios

S_GR:	roadside guardrail
S_NB_Low:	no guardrail, roadside hazard rating 1 or 2
S_NB_High:	no guardrail, roadside hazard rating from 3 to 7

Event Categories

XH:	cross-median head-on event
XNH:	cross-median non-head-on event
RHV:	redirected and hit another vehicle event
MB:	median barrier collision event
SB:	roadside barrier collision event
HR:	non-cross-median high-risk event
MR:	non-cross-median moderate-risk event

KABCO Injury Scale

K: fatality

A: incapacitating injury

B: non-incapacitating injury

C: possible injury

O: property-damage-only

Others

AADT:	annual average daily traffic
ADT:	average daily traffic
AASHTO:	The American Association of State Highway and Transportation Officials
ARIES:	Automated Reporting Information Exchange System
INDOT:	Indiana Department of Transportation
RDG:	Roadside Design Guide
ROR:	Run-off-road
MASH:	Manual for Assessing Safety Hardware
NCHRP:	National Cooperative Highway Research Program
WMS:	Work Management System

ABSTRACT

Zou, Yaotian. Ph.D., Purdue University, December 2014. Performance Assessment of Road Barriers in Indiana. Major Professor: Andrew Tarko.

Road barriers have been used as an effective countermeasure to prevent exposure of errant vehicles to vehicles travelling from the opposite direction or roadside hazards. The objective of this study is to evaluate the in-service safety performance of three types of road barriers (concrete barriers, W-beam guardrails, and high-tension cable barriers) in Indiana using cross-sectional statistical analysis. The evaluation was comprised of three components: 1) the effect on the crash frequency (segment level), 2) the effect on the probabilities of hazardous events (crash level), and 3) the effect on the probabilities of injury outcomes (occupant level). Crash costs, as a measure of overall safety performance, were finally estimated for each studied barrier and non-barrier scenario.

This study found that both the median and roadside barriers were effective in reducing crash costs, and that the former was the more effective of the two. Their main benefits were the reduction of cross-median head-on events for median barriers and reduction of non-cross-median high-risk events (rollover or hitting a sturdy roadside object) for roadside barriers. Crash costs were roughly cut in half with either the use of cable barriers in wide medians (median width larger than 50 feet) or the use of concrete

barriers and guardrails in narrow medians (median width less than or equal to 50 feet). The use of a roadside guardrail resulted in roughly 20% to 30% crash cost reduction.

Median cable barriers were found to be most effective among all the studied barriers due to their smaller increase in crash frequency and less of the severe injury outcomes associated with cable barrier collisions. A cable barrier's offset to the roadway was also investigated in this study. Nearside cable barriers (offset less than or equal to 30 feet) were shown to perform better than far-side cable barriers (offset larger than 30 feet) due to the former's larger reduction in non-cross-median high-risk events such as vehicle rollovers in the median. The findings of this study can help agencies develop: (1) criteria that justify consideration of road barriers, (2) guidelines for selecting the barrier type and related characteristics, and (3) crash cost modification factors to facilitate the cost-effectiveness analysis.

CHAPTER 1. INTRODUCTION

Run-off-road (ROR) crashes, or roadway departure crashes, tend to be severe if the off-roadway environment exposes the occupants of errant vehicles to unforgiving roadside features. ROR crashes combined with other travel lane departure crashes, such as head-on and same-direction-sideswipe, often lead to severe (fatal and incapacitating injury) crashes. These crash types together typically account for over 50% of all fatal crashes in any given year. The worst case scenario is that a vehicle crosses the median or center line and collides with vehicles travelling in the opposite direction.

Forgiving roadside design such as dividing roads with sufficiently wide medians and providing sufficiently wide roadside clear zones have been used to mitigate the occurrence and outcome of roadway departure crashes. While these countermeasures are very efficient in providing enhanced safety, such liberal cross-section dimensions are not a viable option where the land is developed with costly structures or where the terrain topography requires expensive engineering solutions. Another viable countermeasure, the use of road barriers, is becoming increasingly popular in the context of the growing land development along existing roads and the reduced availability of inexpensive land for new roads.

Generally, road barriers can be divided into rigid barriers (e.g., concrete barriers), semi-rigid barriers (e.g. W-beam guardrails), and flexible barriers (e.g., cable barriers) based on the deflection range. Depending on their placement, they can be installed either in the median or along the roadside. Concrete barriers (or barrier walls) and guardrails have been in use for a long time. Concrete barrier walls are mostly used in narrower medians in high-traffic routes. Guardrails are used either in the median or along the roadside with the latter being the majority. High-tension cable barriers were introduced recently to the U.S. and have gained popularity due to their considerable safety benefits. Compared to its predecessor, the low-tension cable barrier, the high-tension cable barrier has a much smaller deflection. High-tension cable barriers are generally used in wider medians, as an alternative to guardrails when the clearance to the obstruction behind the barriers is sufficiently large. The Indiana Department of Transportation (INDOT) began installing high-tension cable barriers in 2006 on interstates roads with wide medians.

Official federal and state guidelines have been established to aid the decision-making process for the use of barriers. The American Association of State Highway and Transportation Officials (AASHTO) Roadside Design Guide (RDG) (AASHTO, 2011) suggests that roadside barriers are to be used based on the premise that striking a barrier is less dangerous than a rollover or striking a roadside object. This premise of a less hazardous barrier may involve a large dose of uncertainty in cases where knowledge is limited. To reduce this uncertainty, there is a need for research on the differences in the risk and severity of the injuries associated with barriers and various roadside hazard conditions.

According to the RDG, a median barrier is optional when the median width is 30 to 50 feet and is not normally considered when the median width is larger than 50 feet. However, the use of road barriers has widened during the last several years and some states have begun to install or have installed median barriers on medians wider than 50 feet (Ray et al., 2009). For cable barriers in particular, most states now recommend their use in medians of 40 to 75 feet wide (Sheikh et al., 2008).

The expanded scope of the application of median barriers and the recent popularity of high-tension cable barriers have provided designers with more viable barrier alternatives. Understanding the safety performance of various types of barriers under different barrier placement setups in various conditions is important. More than one type of barrier may be used for the given traffic, roadway cross-section, and roadside hazard conditions. For instance, both high-tension cable barriers and W-beam guardrails could be viable median barrier alternatives for a wide median (e.g., 60 feet), whereas both concrete barrier walls and W-beam guardrails could be considered in a narrow median (e.g., 30 feet). Careful consideration of the alternatives is required before a barrier type is selected, but once a barrier type is selected, its proper placement is also worthy of consideration.

Uniform guidelines were established to assess the structural performance of road barriers through full-scale crash tests. Although the evaluation based on the testing results are necessary at the beginning stage of a new or modified barrier design, the real-world barrier application conditions are so complex that the actual barrier performance should be obtained by in-service evaluation. Unlike the standard tests which measure barrier performance under specified impact angles and vehicle types, in-service performance evaluation focuses on the observed average safety performance. Moreover, in-service performance evaluation can lead to reliable cost-benefit analyses with information on installation, maintenance, and repair costs. In-service evaluation is particularly useful in an agency's decision-making on whether or not to use barriers, as well as what barriers should be used under given roadway and roadside characteristics.

Thus, the objectives of this study are to:

1) Assess the in-service safety performance of barriers based on the comparison of crashes with and without barriers under similar roadway conditions (cross-sectional analysis).
2) Compare the in-service safety performance among different types of barriers and different placement setups.
3) Develop statistical models and procedures to predict the safety benefits due to barrier treatments.
4) Propose recommendations on whether, where and which type of barriers should be installed.

The studied barriers include median and roadside barriers. They are composed of three types: concrete barriers, guardrails, and high-tension cable barriers. These are all longitudinal barriers, and do not include barrier end treatments, noise barriers, and temporary work zone barriers. The roadway segments with/without barriers include the INDOT-administered divided freeways and rural/sub-urban non-freeway roads. The studied crashes are barrier-relevant crashes and include barrier collision crashes, cross-median crashes, and fixed roadside object collision crashes. Off-roadway rollover crashes and crashes in which vehicles run off the roadway, get redirected back to the roadway, and collide with other vehicles are also included. The barrier-relevant crashes include both single and multiple vehicle crashes.

This thesis is divided into nine chapters and two appendices:

- Chapter 2 reviews the literature addressing the use of road barriers and in-service performance evaluation of them.
- Chapter 3 introduces research approaches applied in this study, which includes the research tasks, a flowchart of the barrier work progress, and an overview of the utilized statistical models and simulation.
- Chapter 4 details the collection, cleaning, and basic summary of the data needed.
- Chapter 5 presents the analysis of the change in crash frequency due to barriers and the developed crash frequency model.
- Chapter 6 analyzes the effect of barriers on the probability of hazardous events and discusses the developed event model.
- Chapter 7 presents the injury analysis and the developed injury model, which addresses how hazardous events relevant to barriers change a vehicle occupant's probability of injury.
- Chapter 8 provides the results of the statistical simulation to estimate the overall safety performance of barriers in terms of crash costs.
- Chapter 9 summarizes the main findings and contributions of this study.
- Appendix A provides the instruction manual for selecting homogeneous segments.
- Appendix B lists the ROR related variables extracted from the crash reports.

CHAPTER 2. LITERATURE REVIEW

This chapter comprehensively reviews the literature addressing the use of road barriers and in-service performance evaluation of them. The current relevant guides and manuals at the federal and state levels are reviewed first, followed by a review of the findings to date regarding in-service performance evaluation. The chapter concludes with a discussion on the limitations of previous research and how this study would fill in the gaps.

2.1 Official Guides and Manuals

2.1.1 Crashworthy Performance Evaluation

The American Association of State Highway and Transportation Officials (AASHTO) Manual for Assessing Safety Hardware (MASH) and NCHRP Report 350, "Recommended Procedures for the Safety Performance Evaluation of Highway Features" (Ross et al., 1993), provide a uniform standard for full-scale crash testing and evaluating procedures for new or modified road barriers prior to extensive installation of them. MASH replaced and updated NCHRP Report 350. As of January 1, 2011, new roadside safety hardware must meet the MASH criteria, while products accepted under NCHRP Report 350 before that date are not required to be retested under MASH. Six test levels were established to represent the crashworthy performance of barriers under different combinations of speed and impact angle. Crashworthy performance was represented by the occupant risk, the structural integrity of the barrier, and the post-impact behavior of the vehicle.

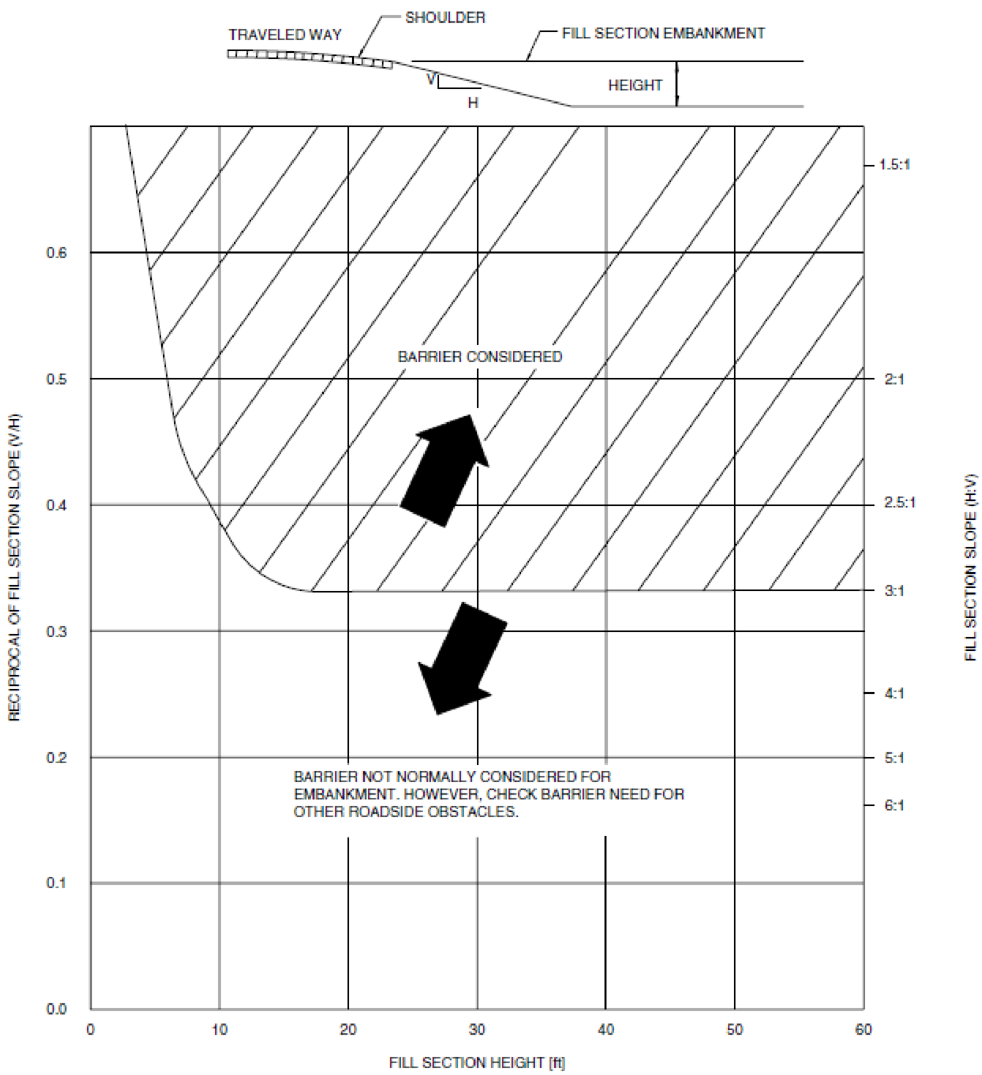


Figure 2.1 Roadside Barrier Consideration for Embankments

(AASHTO, Roadside Design Guide, 2011)

2.1.2 Barrier Use Guidelines

The AASHTO Road Design Guide (RDG) provides guidelines and recommendations on the use of both roadside barriers and median barriers. The RDG defines a roadside barrier as “a longitudinal barrier used to shield motorists from natural or man-made obstacles located along either side of a traveled way”. Roadside barriers are generally considered when the consequences of running off the roadway without the protection of barriers are believed to be more serious than barrier collisions. Embankments and roadside obstacles are the two most common conditions that need to be shielded by roadside barriers. Figure 2.1 shows the RDG’s suggested criteria for the barrier need based on the embankment characteristics.

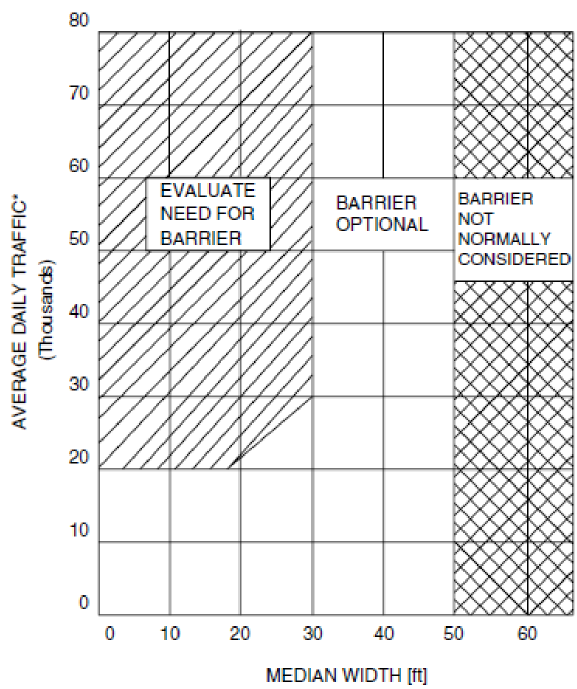


Figure 2.2 Median Barrier Guidelines on High-speed, Fully Controlled-access Roadways (AASHTO, Roadside Design Guide, 2011)

Median barriers are used to separate opposing traffic on divided highways and redirect vehicles striking the barriers from either side. The RDG provides recommendations on the use of median barriers based on the average daily traffic (ADT) and median width as shown in Figure 2.2. The RDG also indicates that some states have expanded the use of median barriers due to the increased number of observed cross-median crashes. A cost/benefit analysis is recommended to justify the decision to expand the use of median barriers.

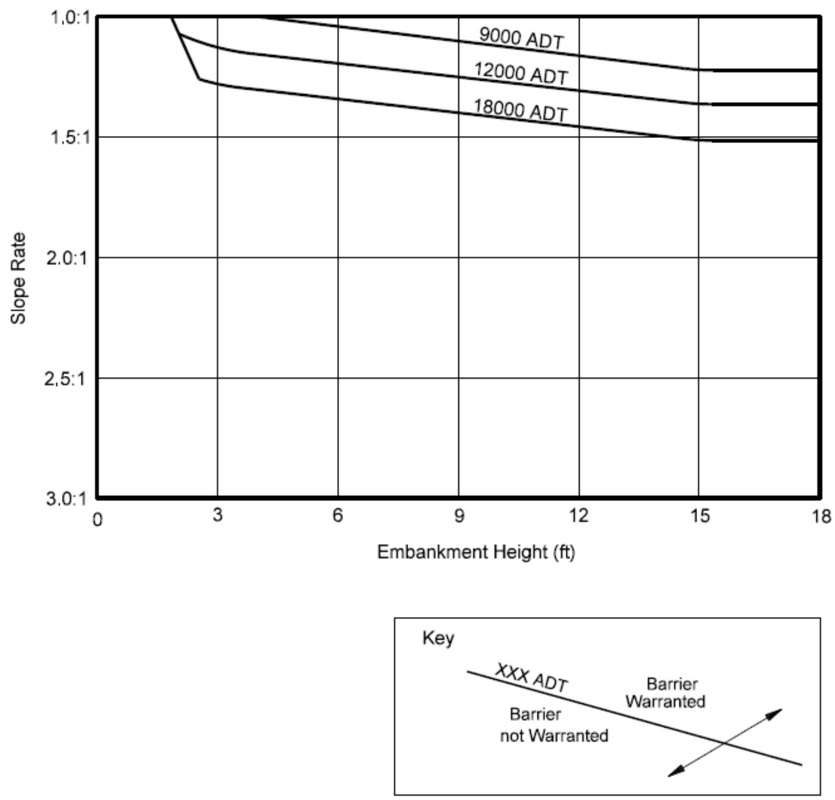


Figure 2.3 Roadside Barrier Warrant for Embankment (Two-lane, Two-way, 35 or 40mph) (Indiana Design Manual, 2013)

The Indiana Design Manual (Indiana DOT, 2013) adopted barrier warrant criteria similar to the RDG but classified the criteria into more roadway scenarios. For roadways of 4 or more lanes (divided and undivided), the warrant of roadside barriers based on the embankments is the same as that for the RDG as shown in Figure 2.2. For two-lane two-way roadways, it also considers the ADT and design speed as criterions. Figure 2.3 is an example of roadside barrier warrant for embankments on two-lane two-way roadways with design speed 35mph or 40mph.

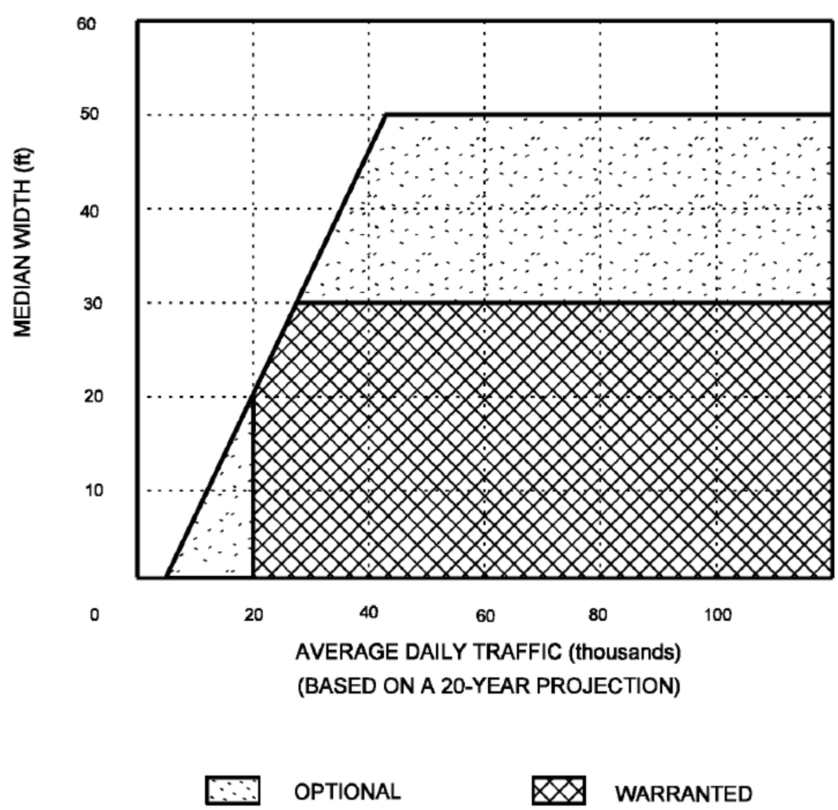


Figure 2.4 Median Barrier Warrants (Indiana Design Manual, 2013)

The median barrier warrant in the Indiana Design Manual, shown in Figure 2.4, is similar to the RDG, but the traffic criteria in the Indiana Design Manual is the 20-year projected ADT while the RDG criteria is the 5-year projected ADT. The Indiana Design Manual also requires a median barrier be used on a freeway or expressway with a design speed of 50mph or higher and requires median crossings at least one mile apart.

2.1.3 Summary of the Official Guides and Manuals

The NCHRP Report 350 and MASH established a standard procedure to test the performance of road barriers before they are extensively used in the field. They classified barriers into different test levels from which decision makers can choose based on the local traffic composition and geometrics. However, the crash tests were limited to certain types and weights of test vehicles, and the testing was conducted under prespecified impact angles, which might not represent typical in-field impacts from errant vehicles. Thus, both guides indicate that in-service evaluation is necessary and important in assessing the efficiency of a roadside product and providing in-depth knowledge.

Guidelines and warrants on the use of median and roadside barriers are available in the RDG and the Indiana Design Manual. The ADT and median width are used as the criteria for considering median barriers; and the embankment height, embankment slope, and roadside obstacles are for considering roadside barriers. These guidelines not only help agencies properly select and install barrier systems but also provides the structural and safety characteristics of different types of barriers.

It is important to note that for median barriers, many states have expanded their use and thus have developed their own specific median barrier guidelines, with consideration given for criteria such as median crossover history and number of fatalities in the development process. Particularly for cable barriers, many states have installed them on wide medians ranging from 40 feet to 75 feet (Sheikh et al, 2008). Due to its popularity and rather short history compared with other median barriers, it is important to investigate their on-field performance.

Almost all of the aforementioned guidelines and manuals state that there is no one-size-fits-all recommendation on the use of barriers and suggest conducting in-service evaluations of the safety performance of barriers to validate their cost-effectiveness for local application. The RDG recommends that the in-service evaluation include factors such as traffic volumes, vehicle classifications, median crossover history, crash incidents, vertical and horizontal alignment relationships, and median-terrain configurations.

2.2 In-Service Evaluation

According to NCHRP Report 490, "In-Service Performance of Traffic Barriers" (Ray et al., 2003), the purpose of in-service evaluations of roadside features such as road barriers is to:

- Determine how barriers perform under field conditions
- Assess how full-scale crash tests are representative of the way collisions occurred under field service conditions

As NCHRP Report 490 pointed out, although the importance of in-service evaluation is well recognized, there is no universal formal process at the current time for in-service evaluation; the procedures and methods that have been used are ad-hoc and provide varied results.

In-service evaluation of the safety performance of road barriers generally includes the assessment of the crash frequency, crash injury-severity and cost-effectiveness. Since the use of barriers reduces the recovery zone for errant vehicles, many states have found that the crash frequency has increased since barriers were installed. However, not all types of crashes have increased proportionally. Rather, certain crashes that are normally associated with more severe injuries (e.g., cross-median crashes, fixed roadside object collisions, etc.) have greatly reduced, while some less severe crashes began to occur (e.g. barrier collisions) or increased (e.g. same direction side swipe crashes). Besides, how forgiving the barriers are compared to the hazardous conditions they are installed to prevent also need to be investigated given that the barriers themselves are also hazards. Also, installing and repairing barriers can be costly so the cost-effectiveness analysis is important in justifying the barriers' benefits in improving the safety.

2.2.1 Crash Frequency

Past research has found that the number of severe crashes have been reduced with the use of barriers. Due to the trend of forgiving roadside design, the majority of the recent research has focused on the performance of cable barriers. Sheikh et al. (2008) summarized the advantages of using high-tension cable barriers as follows: low installation cost, low impacts on errant vehicles, minimal visual intrusiveness, and large sight distance; while the disadvantages include high damage cost, great deflection distance, periodic re-tensioning, and their ineffectiveness after impact.

Past research regarding the effect of barriers on crash frequency mostly has mainly focused on certain types of crashes of interest, rather than all relevant crashes. In other words, crashes first were categorized into several types and then one or several crash types of interest was selected for frequency analysis. Several common ways to divide crashes include: 1) by the manner of collision or hazardous events, 2) by the number of number of vehicles involved and 3) by the vehicle type.

Frequency change of crashes by manner of collision or hazardous event

Crashes of interest considering manner of collisions or hazardous events include ROR crashes, head-on crashes, cross-median crashes, fixed object collisions, etc. In North Carolina, one of the states that pioneered the use of cable barriers, Hunter et al. (2001) found that at locations with cable barriers installed, the number of total crashes, rear-end crashes, ran-off-road-left and hit-fixed-object crashes increased. However, the serious crashes, such as head-on crashes, decreased, and thus the overall safety was shown to have improved based on the equivalent property damage only index.

Donnell and Manson (2006a) investigated the relationship between median-related crashes and geometric and traffic operational variables. Their modelling results revealed that the frequency of cross-median crashes and median barrier crashes decreased with increases in the median width and barrier offset. Another study (Donnell and Manson, 2006b) investigated the frequency of median barrier crashes on Pennsylvania interstate highways. Crash frequency models based on negative binomial regression were developed for the non-toll portion of the Interstate highway and the Turnpike toll road respectively. The modelling results indicated that the presence of interchange entrance ramps increased the median barrier crash frequency on the non-toll portion and decreased the crash frequency on the Turnpike toll road. In addition, an increase in the speed limit was found to increase the frequency of median barrier crashes on the non-toll portion.

Chimba et al. (2014) investigated the factors that affect the frequency of median-related crashes. They found that increases in traffic volume and the presence of curves on a median barrier section increased the frequency of median crashes. The results also indicated that the frequency of median barrier crashes increased with higher differential elevation between opposite travel lanes.

Frequency change of crashes by number of vehicles involved

Tarko et al. (2008) investigated the impact of median designs on crash frequency and severity. The investigated crashes were classified as three types: single-vehicle, multiple-vehicle same direction, and multiple-vehicle opposite direction. The authors found that reducing the median width without adding barriers increased the crash severity, and reducing the median width and installing concrete barriers eliminated opposite direction crashes, but in so doing, the frequency of single vehicle crashes doubled and the crash severity tended to increase. Before-and-after studies conducted by Villwock et al. (2011) indicated that installing high-tension median cable barriers can eliminate 94% of multiple vehicle opposite-direction crashes but can increase single vehicle crashes on wide, depressed medians by 70%.

Frequency change of crashes by vehicle type

Although most of the past barrier studies investigated barrier performance based on the fact that the majority of the involved vehicles were passenger cars and trucks, a few studies focused on the safety performance of barriers on motorcycle crashes in particular.

Daniello and Gabler (2011a) investigated the effect of the barrier type on motorcycle-barrier crashes in North Carolina, Texas, and New Jersey and concluded that motorcycles comprise only 3% of the vehicles on the road but account for nearly half of all fatalities in guardrail collisions and 22% of the fatalities in concrete barrier collisions.

Jama et al. (2011) conducted a retrospective study on fatal motorcyclist-road barrier collisions in New Zealand and Australia and found that the fatalities involving W-beams, concrete, and wire rope barriers accounted for 72.7% (with a total length of 5,565.4 km), 10,4% (with a total length of 672.9 km), and 7.8% (with a total length of 1234.6 km), respectively. Their results also suggested that inappropriate speed and the consumption of alcohol and drugs were the major causes of motorcyclist-road barrier fatalities.

2.2.2 Crash Injury

The objective of most injury analysis studies is to identify the changes in the probability of certain injury outcomes due to the use of barriers. Most studies classify crashes based on the KABCO scale; and the original levels are most often combined due to the limited number of severe injuries (e.g., K+A, B+C, O).

Hu and Donnell (2010) developed a nested logit model to investigate median barrier crash severity on rural divided highways in North Carolina. The results indicated that collisions with cable median barriers tend to result in less severe injuries (i.e., fatality, incapacitating injury and non-incapacitating injury) than collisions with concrete or guardrail median barriers. They also found that the probability of severe outcome crashes decreased with increases in the median cable barrier offset and the use of flatter foreslopes. Based on an ordinal logistic regression model, injury analysis on cross-median crashes and median-related crashes by Donnell and Manson (2006a) found that drivers under the influence of drugs and dry pavement surfaces are more likely to result in fatality and other injury. An analysis of fatal motorcycle collisions was conducted by Daniello and Gabler (2011b), which indicated that collisions with trees, guardrails, and concrete barrier, respectively, were 15 times, 7 times, and 4.1 times more likely to be fatal than collisions with just the ground.

Based on the results of a nested logit model, Holdridge et al. (2005) concluded that striking concrete barriers and guardrails could reduce the probability of incapacitating and non-incapacitating injuries when compared to collisions with fixed roadside objects. Martin et al. (2013) found that concrete barriers are less effective than W-beam guardrails in reducing cross-median crashes.

Zou et al. (2014) investigated the risk of injury among different hazardous events related to barriers; and their results indicated that from the viewpoint of reducing injury risk, near-side cable barriers (offset between 10 and 29 feet) performed best, followed by far-side cable barriers (offset at least 30 feet), guardrails, and concrete barriers.

2.2.3 Cost Effectiveness

Cost-effectiveness studies are conducted based on the results of crash frequency and injury analysis. Crashes with certain injury outcomes or with certain crash types are converted to monetary dollars. The change in the monetary values of total crashes with/without barriers is the benefits of the barrier. After considering the costs of barrier installation, maintenance, and crash repair in a specified service life, a benefit-cost ratio is provided.

Miaou et al. (2005) conducted a benefit-cost analysis and a sensitivity analysis to develop the guidelines for concrete and high-tension cable barriers. They obtained the mean benefit-cost ratios between high-tension cable barrier and concrete barriers.

Donnell and Manson (2006a) conducted a benefit-cost analysis on the use of median concrete barriers and W-beam guardrails and developed median barrier placement guidelines based on the benefit-cost ratio. The developed guidelines were based on the directional average daily traffic and median width. They also provided a crash-based warrant for the use of median barrier on medians with width larger than 70 feet.

Sicking et al. (2009) examined crashes that occurred in Kansas and developed guidelines on the use of median cable barriers based on the Roadway Safety Analysis Program. Using the obtained benefit-cost values under different combinations of average daily traffic and median width, they suggested that a median cable barrier generally should not be considered in medians wider than 70 feet.

Chitturi et al. (2011) developed comprehensive injury costs for cross-median crashes and median barrier crashes; and their results showed that the injury costs for concrete median barriers were roughly 20% of that of multiple vehicle cross-median crashes and 50% of single vehicle cross-median crashes. They recommended the use of crash type-specific costs.

2.2.4 Summary of In-service Evaluation Studies

Previous research has studied the in-service safety performance of road barriers from various perspectives. The safety performance of high-tension cable barriers have been the recent research focus. The in-service study can be generally divided into three areas: 1) crash frequency, 2) crash injury and 3) cost-effectiveness.

For crash frequency analysis, extensive studies have focused on the use of median barriers, especially median cable barriers. Many studies reported that cross-median crashes were substantially reduced by the use of median barriers. They have developed statistical models to identify the factors that affect the median barrier crash frequency. Before-after or cross-sectional approaches have been used. However, a limited number of studies examined crashes that were affected by barriers other than cross-median crashes and median barrier crashes. Even for cross-median crashes, however, many of the studies were not able to properly handle those crashes using statistical models due to their infrequency. Analysis based on only a portion of the crashes that are affected by barriers might either underestimate or overestimate a barrier's performance.

Injury analysis studies have found that the use of barriers can reduce the probability of fatalities or severe injuries. However, all the past barrier-related injury research reviewed in this study was based on the crash level. That is, they did not analyze the personal injury directly but instead used the most severe injury level of all the occupants involved in a crash to represent the injury level of the crash and then analyzed the barrier's effect on the crash injury.

Crash level injury analysis is associated with limitations, particularly in the context of analyzing the effect of barriers. The primary type of crash that barriers are intended to prevent is cross-median head-on crashes; these involve more than one vehicle and very likely have many occupants severely injured at the same time. Since the crash level injury depends on the maximum injury of all the occupants only and does not consider how many occupants suffered the maximum injury, using crash level injury analysis underestimates the actual severity of cross-median head-on crashes. Even for studies that were outside the scope of road barriers but addressed the individual occupants, they typically have focused on specific vehicle occupants, who might be the driver (Ulfarsson and Mannering, 2004; Kockelman and Kweon, 2002) or the front seat passengers (Hutchinson, 1986; Shimamura et al., 2005). Only a few studies investigated the injury of all the vehicle occupants and included Eluru et al. (2010) and Zhu and Srinivasan (2011), both of which recognized the fact that it may not be possible for the injury level of specific vehicle occupants to accurately represent the overall injury severity.

As far as cost-effectiveness analysis, most of the previous studies provided benefit-cost ratios under different scenarios of AADT and median width. Some of them also included the history of cross-median crashes to supplement their developed guidelines based on benefit-cost ratios. The key is to calculate the reduction of crash costs due to the use of barriers.

Overall, most of the past studies focused on particular types of barriers or particular types of crashes (e.g., cross-median crashes, cable barriers, motorcycles, etc.). They did not fully capture the barriers' effects on all the involved vehicle occupants. Furthermore, the effect of barrier placement factors, such as the barrier's offset, was not addressed by most of past studies due to the lack of data (Hu and Donnell, 2010). Ray et al. (2009) pointed out that the placement of median cable barriers considerably varied among states. In some states, cable barriers are placed almost in the center of the median, whereas, in other states they are offset at least six feet from the centerline of the ditch. The authors suggested more research on this subject.

Given the limitations found in past studies, the present study aims to analyze the safety performance of barriers in a broader context in order to conduct an overall assessment of various barrier and non-barrier alternatives with as much information as possible. Both median and roadside barriers are analyzed together, which includes three types of barriers (concrete barriers, guardrails, and cable barriers); and the offsets of cable barriers are also investigated.

All the crashes relevant to the various barriers are clearly classified and analyzed, including both single and multiple vehicle crashes and both severe crashes, such as cross-median head-on, and non-severe crashes, such as hitting a road sign post. The risk of injury for all the vehicle occupants is estimated, and the crash costs for various barrier and non-barrier scenarios are calculated and compared.

The results of this dissertation will not only shed light on the overall safety performance of barriers but also will provide an applicable procedure for highway agencies to quantify the benefits of barriers in terms of saved crash costs.

2.3 Modelling Approaches

2.3.1 Crash-frequency Modelling

Crash-frequency modelling in traffic safety has focused on the association between factors of interest with the total number of crashes for a given space (e.g., roadway segment or intersection) over a given time period (Lord and Mannering, 2010; Mannering and Bhat, 2014). Since the crash count is a non-negative integer, simple linear regressions are often not appropriate and count models, as a type of generalized linear models, have been applied instead. As the simplest generalized linear model, the Poisson model, has been criticized for its assumption that the conditional mean is equal to the conditional variance, which is often violated due to the over- and under-dispersion exhibited by the crash data. Thus, negative binomial models (Miaou, 1994; Poch and Mannering, 1996), which can be deemed as extensions of Poisson models by including a gamma distributed error to its mean, have been widely used due to their capability of handling over-dispersed data.

Other extensions based on Poisson models include the Conway-Maxwell-Poisson model (Lord et al., 2008; Lord et al., 2010), the double Poisson model (Zou et al., 2013), the hyper-Poisson model (Khazraee et al., 2014), the Poisson-lognormal model (Park and lord, 2007), the Poisson-Weibull model (Cheng et al., 2013), among others. The Conway-Maxwell-Poisson model, double Poisson model, and hyper-Poisson model can handle both over- and under-dispersion, although the under-dispersion is rarely seen in crash data. Extensions of the negative binomial models include the negative binomial-Lindley model (Geedipally et al., 2012). To take care of a large number of zero counts found in some crash data (particularly for a short segment in a short period), zero-inflated Poisson and negative binomial models (Miaou, 1994; Shankar et al., 1997; Carson and Mannering, 2001; Lee and Mannering, 2002) have been applied due to their improved statistical fit; but their use in highway safety should be accompanied with caution since the dual-state data generating process in the zero-inflated models might not reflect the actual safety situation (Lord et al., 2005; Lord et al., 2007).

Handling of the unobserved heterogeneity across observations has been the focus of recent advancements in crash-frequency modelling. Two dominant approaches are random parameters frequency models (Anastasopoulos and Mannering, 2009; Mitra and Washinton, 2012; Chen and Tarko, 2014) and finite mixture/Markov switching frequency models (Park and Lord, 2009; Malyshkina and Mannering, 2010). The major difference between the two approaches is that the former assumes a continuous distribution (e.g., normal distribution) on the parameters for different observations while the latter uses a discrete distribution (e.g., distinct subgroups). Recent advancements also include non-parametric approaches such as the artificial neural network (Chang, 2005) and the support vector machine (Li et al., 2008). Although these methods have weaker assumptions and tend to provide a better fit, the interpretability is relatively poorer and the estimation is more complex.

2.3.2 Crash-severity Modelling

Crash-severity studies typically focus on the association between the probability of an observation (normally a crash) resulting in a certain injury outcome and factors of interest (e.g., vehicular and occupants' characteristics) conditioned on the crash having occurred (Savolainen et al., 2011). The severity analysis is often conducted at the crash level, and the injury outcome of a crash is represented by the injury outcome of the most severely injured occupant. Since the injury outcome is often measured based on the injury scales (e.g., KABCO scale) which have more than two levels, it is tempting to use the discrete outcome models such as the ordered logit/probit models (Khattak, 1998; Abdel-Aty et al., 2005) that can take care of the natural ordering. However, ordered discrete outcome models should be used with caution due to their problems related to the underreporting of crash data and its restriction on the direction how variables affect ordered outcomes (Washington et al., 2011).

Extensions based on the ordered logit/probit have focused on addressing the endogeneity (de Lapparent, 2008), the unobserved heterogeneity across observations (Srinivasan, 2002), the heteroskedasticity in error terms (Quddus et al., 2010), and the correlation among occupants involved in the same crash (Eluru et al., 2010).

Unordered discrete outcome models also have been widely used to model injury outcomes since they have fewer restrictions and tend to be more robust, although their use does not take advantage of the information in ordering. The basic unordered discrete outcome models are binary logit/probit models (Shibata and Fukuda, 1994; Lee and Abdel-Aty, 2008) and multinomial logit/probit models (Shankar and Mannering, 1996; Malyshkina and Mannering, 2008). The binary logit model often has been used when the number of observations for certain injury levels is limited and collapsing the categories will lead to binary outcomes such as injury vs. non-injury. The use of the multinomial logit model has been based on satisfaction with the independence of irrelevant alternatives (IIA) assumption (Washington et al., 2011). The IIA assumption can be tested using the nested logit model (which can be seen as a generalization of the multinomial logit model) and the violation of the IIA assumption would lead to the use of the nested logit model or other models that relax the IIA assumption (e.g., mixed logit model).

Models that can handle the unobserved heterogeneity across observations such as the mixed logit model (i.e. random parameters logit models) (Milton et al., 2008; Anastasopoulos and Mannering, 2011) and the finite mixture/Markov switching multinomial model (Eluru et al., 2012; Malyshkina and Mannering, 2009) have been the recent focus of modelling crash-severity. The mixed logit model is particularly noteworthy since it allows the unobserved effects of alternatives to be correlated and thus does not require a test on IIA assumption. More generalized and flexible models (Xiong and Mannering, 2013; Xiong and Mannering, 2014) in modelling injury also have been investigated by combining random parameters models with finite-mixture/Markov switching models. Moreover, some researchers proposed the use of non-parametric methods (Chimba and Sando, 2009; Abdelwahab and Abdel-Aty, 2001). As previously mentioned, non-parametric methods are superior in prediction but not in making inferences.

2.3.3 Summary of Modeling Approaches

Generally speaking, recently developed crash frequency and injury models have shown advantages in handling datasets with particular characteristics (e.g., low mean or small sample size) and gaining more insights (e.g., multiple-stage data generating process or unobserved heterogeneity). However, the estimation of those models is more complex and often there is no closed form solution to maximum likelihood estimation. They may need to be estimated using Bayesian methods (e.g., Markov Chain Monte Carlo) or based on other numerical methods, which are likely to encounter convergence problems.

Furthermore, the results of some models may not be easily transferable to other datasets (Lord and Mannering, 2010).

The event outcomes can be estimated using most of the approaches applied to model injury outcomes from the modelling point of view. However, limited research has been found in this area. This might be due to two reasons: 1) the hazardous events are various and it would be difficult and impractical to estimate each of them without combining some of them; and 2) much research focuses on crashes with a particular type of event, and thus there is no need to consider other events.

However, various hazardous events are affected by the use of barriers and they vary considerably in terms of the associated risk of injury when a vehicle occupant gets involved in them. So the inclusion of the effect of barriers on the change in the probabilities of all the relevant events is crucial to the overall performance evaluation.

Different from previous safety treatment studies which just model the crash frequency and injury change due to the treatment, this study introduces the modelling of events as the important link between the frequency modelling and injury modelling. All the events affected by barriers or events might have been affected if a barrier had been present will be analyzed in this study. This not only will provide more insights on the overall effect of barriers but also ensure the performance evaluation is not under- or over-estimated.

The final model selection for this study will consider the data availability, the sample size, the interpretability of modelling results, and the estimation complexity. More details can be seen in relevant chapters.

CHAPTER 3. RESEARCH APPROACH

This chapter is an overview of the research approaches applied in this study, which includes a tree of events involved in the crash process, a categorization of barrier and non-barrier scenarios, a definition of barrier-relevant crashes, and an overview of useful statistical models and simulation.

3.1 Safety Effect of Road Barriers – Concept

To understand the complete effect of barriers on safety, let us first analyze the sequence of possible hazardous events and outcomes which a vehicle might encounter after its departure from the roadway assuming there is no barriers present (see Figure 3.1). When a vehicle departs from the roadway for some reason (e.g., driver fatigue, bad weather, etc.), it becomes a run-off-road (ROR) vehicle. Then, if the occupants do not sustain injury and the driver is able to redirect the vehicle back to the roadway, it is very likely that the driver will not report this to police and thus no information is recorded for this unreported crash. Therefore, this study only analyzes reported crashes due to the lack of information for unreported crashes.

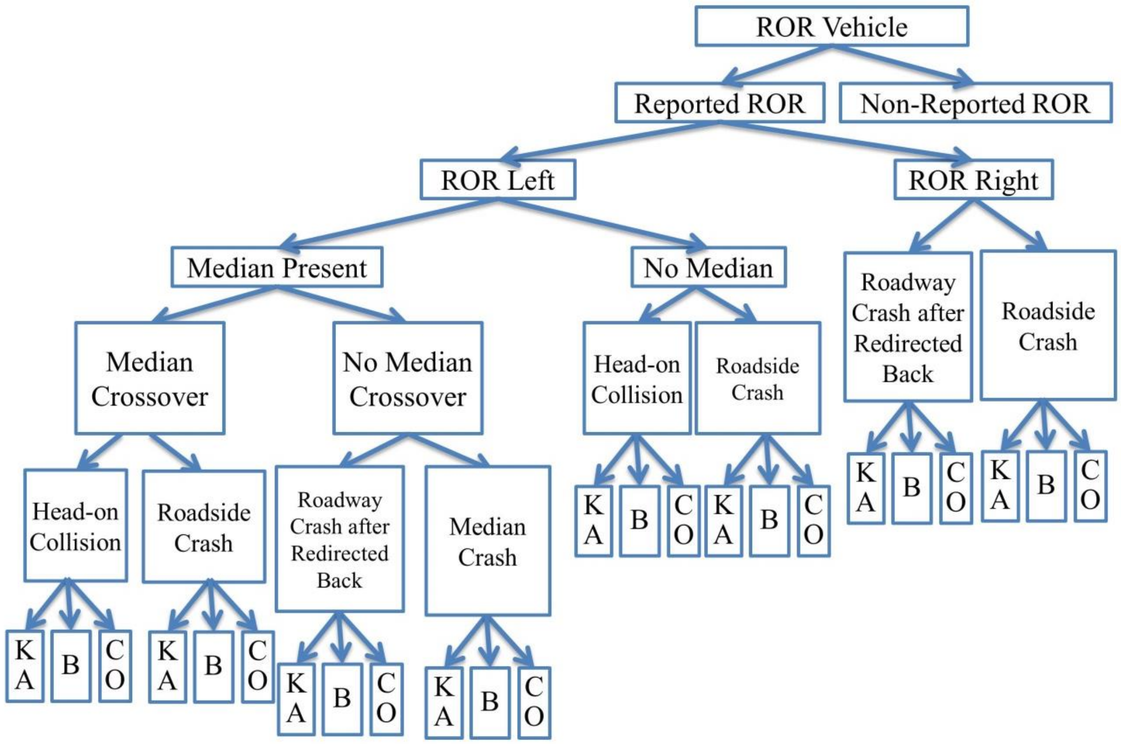


Figure 3.1The Tree of Events Affected by Barriers

The vehicle may depart the roadway to the left or right. On the right, the vehicle may collide with roadside objects or may roll over the embankment and then be involved in a roadside crash. The vehicle also may be redirected back to the roadway (by driver correction or by rebounding from a roadside object collision) and subsequently collide with a vehicle moving on the roadway, which results in a roadway crash. If the vehicle departs the roadway to the left and there is no median on the roadway, it may collide head-on with a vehicle moving in the opposite direction. Another possibility is that the vehicle continues moving until it collides with a roadside object or rolls over an embankment. If there is a median present, the vehicle may cross the median, which may collide head-on with a vehicle in the opposite direction or may continue moving until it collides with a roadside object or rolls over an embankment. If the vehicle does not cross the median, it may roll over in the median or collide with an object in the median and then involved in a median crash. In summary, the occupants in a ROR vehicle may be involved in various hazardous events with consequent injury outcomes.

The presence of barriers changes the probability of certain events and the probability of their outcomes. According to the tree of events shown in Figure 3.1, barriers affect the number of ROR vehicles reported because the use of barriers reduces the recovery zone. Barriers also are assumed to change the probability of certain crash events; for example, cross-median and median rollover events are reduced or eliminated. On the other hand, barriers may redirect vehicles back to the roadway and thereby may increase the probability of a roadway crash. Due to such a redistribution of the probabilities of crash events, the overall injury outcomes may consequently change.

The complexity of the tree of events discussed above is simplified into three components to reflect the safety effect of barriers from the modelling point of view. A statistical model is developed for each of the three components:

- The effect of barriers on the crash frequency
- The effect of barriers on the hazardous events
- The effect of hazardous events on the injury outcomes

Statistical simulation then is conducted to assess the overall safety performance of the studied barrier and non-barrier scenarios by incorporating the results from the individual models.

3.2 Barrier and Non-barrier Scenarios

This study is interested in the safety performance of three types of barriers: concrete barriers, W-beam guardrails, and high-tension cable barriers on divided roads. The placement of barriers varies even within the same barrier type. Different barrier and non-barrier scenarios can be divided based on their on-field use in Indiana. They can be used to represent the median and roadside environment of a directional roadway segment.

It is assumed that the median environment (may include a median barrier) and the roadside environment (may include a roadside barrier) for a given directional roadway segment are independent, with each of them represented by a set of explanatory variables in the modelling process. Each set of variables is composed of several dummy variables representing different barrier and non-barrier scenarios, with one scenario selected as the reference condition or reference category.

In this study, the median environment is divided into six scenarios (or categories):

- M_NB_Nar: median 50 feet or narrower and no median barrier.
- M_NB_Wide: median wider than 50 feet and no median barrier.
- M_BW: median concrete barrier wall placed in the center of a narrow median.
- M_GR: median guardrail placed in the center of a median or at the nearside edge.
- M_CB_Near: median cable barrier (near-side) with a lateral clearance 30 feet or less to the travelled way.
- M_CB_Far: median cable barrier (far-side) with a lateral clearance more than 30 feet to the travelled way

The roadside environment is divided into three scenarios (or categories):

- S_GR: roadside guardrail.
- S_NB_Low: no guardrail, roadside hazard rating 1 or 2.
- S_NB_High: no guardrail, roadside hazard rating from 3 to 7.

See the Highway Safety Manual (AASHTO, 2010) for the roadside hazard rating index. Each combination of a median category and a roadside category represents a unique scenario. Thus, a total of 6*3=18 different median and roadside scenarios (i.e., barrier and non-barrier scenarios) are identified, which is the maximum number of possible scenarios. The number of viable scenarios depends on the existing roadway and roadside characteristics.

3.3 Barrier-relevant Crashes

It is important to emphasize that this study does not analyze all the crashes that occur on the segments where data are collected but rather focuses on the barrier crashes that are relevant to the objectives of the study. In this study, we define barrier-relevant crashes as those whose outcomes are affected or may have been affected by a barrier had the barrier been installed. Barrier-relevant vehicles, occupants, and events are defined in a similar way. In a barrier relevant crash, at least one vehicle 1) directly collides with a road barrier or 2) collides with a roadside object or becomes involved in an crash event that may have been prevented had a barrier been installed.

Following this definition, crashes that involve collisions with barriers, rigid roadside objects (e.g., trees, utility poles) and semi-rigid roadside objects (e.g., highway traffic signs and fences) are relevant as well as those non-collision events such as running off the roadway and then rolling over and running off the roadway without specifying that any objects are hit. It is important to note that not all of the rigid or semi-rigid object collisions are relevant. The crashes that involve collisions with roadside objects that are not able to coexist with barriers (e.g., bridge rail, work zone facilities) are considered irrelevant and should be excluded from the analysis.

Identifying the barrier-relevant vehicles in a multi-vehicle crash can be complicated because it is likely that a portion of the involved vehicles are not barrier-relevant vehicles. For example, when an on-road vehicle makes an unsafe lane change, a following vehicle might have minor contact with that vehicle, lose control, leave the roadway, and collide with a tree. In this case, the following vehicle is obviously a barrier-relevant vehicle while the on-road vehicle is not because the on-road vehicle would have had the same outcome had a barrier been there.

However, this does not necessarily suggest that all the on-road vehicles involved in a barrier-relevant crash are irrelevant. For a multi-vehicle crash in which a vehicle run off the roadway, crosses the median, and collides head-on with another on-road vehicle in the opposite direction, both vehicles are barrier-relevant vehicles since a median road barrier could have changed the outcomes for both of them. Another case is when a vehicle leaves the roadway and collides with a barrier, bounces off the barrier and returns to the roadway, and then collides with an on-road vehicle in the same direction. In this case, both vehicles are barrier-relevant vehicles since both of their outcomes may have changed if no barrier had been present.

A detailed procedure of how barrier-relevant crashes are selected based on the available databases in this study is presented in Section 4.4.2.

3.4 Statistical Models

3.4.1 Frequency Model

The purpose of barriers is to alter roadside hazardous events into less hazardous collisions. However, the observed impacts of barriers go beyond replacing hazardous events with less hazardous ones. For example, many researchers observed that the installation of barriers can increase the total number of reported crashes. This observation can be due to following barrier location characteristics: 1) barriers are placed closer to the roadway than the hazardous objects they shield, and 2) continuous barriers may shield a group of point hazards such as trees. Barriers reduce the width of the recovery area and eliminate the chance of missing the roadside hazard. Thus, the risk of striking barriers can increase and the frequency of reported ROR crashes can increase as well.

A negative binomial regression model is developed to estimate the increase in barrier-relevant crash frequency on a segment where the increase was attributed to the installation of barriers. The model is also used to predict the number of barrier-relevant crash frequency on a segment with given roadway and roadside characteristics over a certain period. The details of the frequency model are provided in Chapter 5.

3.4.2 Event Model

Barriers are expected to eliminate or reduce the occurrence of roadside hazardous events such as cross-median events or roadside fixed objects collisions. Although eliminating roadside dangerous events is difficult to accomplish, the risk can be effectively reduced by the use of barriers. However, barriers also can have unintended effects such as introducing barrier collisions and increasing redirected multi-vehicle collisions.

Since barriers have been shown to reduce the risk of hazardous events but may increase additional events, such as redirecting of a vehicle, which may lead to a multi-vehicle collision, it is important to know how those different hazardous events are distributed and what their probabilities are with and without barriers given that a barrier-relevant crash occurs. Therefore, in this study, events with hazards that have similar characteristics are combined to form a relatively smaller number of event categories.

A multinomial logit model with variable outcomes is developed to predict the probability of a barrier-relevant crash resulting in each considered event category on a given segment with given roadway and roadside characteristics. Chapter 6 provides the event model details.

3.4.3 Injury Model

Collisions with barriers supposedly are less risky than the prevented events. Given the fact that a barrier itself is also a hazard which can cause injury on vehicle occupants, there would be no need to consider installing a barrier as a viable alternative if barrier collisions are more likely to be associated with severe outcomes than those hazardous events it prevents. Therefore, an important question to be addressed is how much more forgiving are those barrier collisions compared to the hazardous events?

A binary logistic regression model with random effects is estimated to study the risk of injury associated with various hazardous events faced by vehicle occupants. The response variable has two values: injury (fatal or incapacitating or non-incapacitating) and no confirmed injury (possible injury or property-damage-only). Hazardous events are represented by discrete explanatory variables. The estimated model can predict the probability of injury for a vehicle occupant involved in a given hazardous event.

3.4.4 Overview of Model Input and Output

The developed statistical models in this study included the frequency model, the event model, and the injury model. The modelling form and relevant important setups are as follows.

For the frequency model (count model):

- A negative binomial regression model is used.
- A record in the sample is a directional roadway segment.
- The objective is to predict the number of barrier-relevant crashes on a given segment over a certain time period.
- The response variable is the total number of barrier-relevant crashes that occur over its analysis period.
- The explanatory variables are the traffic, speed limit, and roadway and roadside characteristics, etc.

For the event model (discrete outcome model):

- A multinomial logit model with variable outcome set is used.
- A record in the sample is a crash characterized by its most hazardous event category.
- The objective is to predict the probability of a barrier-relevant crash resulting in different hazardous event categories.
- The response variable is the event category outcome of a barrier-relevant crash.

- The explanatory variables are the traffic, speed limit, roadway and roadside characteristics of the segment, etc.

For the injury model (binary outcome model):

- A binary logit model with random effects on vehicle and segment pair is used.
- A record in the sample is a vehicle occupant involved in a barrier-relevant crash.
- The objective is to predict the probability of injury for a vehicle occupant conditioned on that a barrier-relevant crash has occurred and the most hazardous event is known.
- The response variable is whether or not the vehicle occupant was injured.
- The explanatory variables are the most hazardous event, the type of vehicle, the occupants' demographic characteristics, etc.

3.5 Statistical Simulation

It can be seen that the discussed models are based on different levels of data aggregation: the crash frequency model is at the segment level; the event model is at the crash level; and the injury model is at the occupant level. Each individual model deals with a portion of the overall evaluation of the safety performance of barriers. To model the complete tree of events and their outcomes, all of the developed models should be applied together.

With the barrier and non-barrier scenarios of interest identified, statistical simulation can be conducted to assess the overall safety performance of those scenarios. Starting from a scenario of interest, we can first predict the barrier-relevant crash frequency based on the estimated coefficients in the frequency model. Then we can use the developed event model to predict the proportions of different crash events.

Combining those predicted results can provide us with the number of barrier-relevant crashes classified by events, which we then can convert to the number of occupants classified by events and predict their injury outcomes based on the developed injury model. Finally, crash costs can be calculated to represent the overall safety performance of the scenario of interest. Chapter 8 presents the simulation procedure and the results.

3.6 Chapter Summary

In summary, the first part of the research approach is to develop statistical models that can predict the roadway segment's barrier-relevant crash frequency, the crash's event probability, and the occupant's fatal/injury probability. The barrier-relevant crashes designate not only barrier collision crashes but also those crashes whose collision events and outcomes may have been changed if a barrier had been present. The information for the barrier and non-barrier use can be represented by different median and roadside scenarios. The studied scenarios include the installation of different types of barriers under different offset setups, the use of a wide median or narrow median with no barrier, and the use of a high hazard rating roadside or low hazard rating roadside with no barrier.

The second part of the research approach applies the developed models to segments with different scenarios and conducts statistical simulation to obtain the crash costs for each scenario by incorporating intermediate model-predicted results.

CHAPTER 4. DATA DESCRIPTION

This chapter details the collection, cleaning, and basic summary of the data needed for this study with a focus on the independent data collection procedure on homogeneous roadway segment selection and barrier-relevant crash selection.

4.1 Data Sources and Major Collection and Processing Steps

The data used for this research include those directly taken from the INDOT current existing databases and those independently collected for this particular research. The existing electronic INDOT databases provided all the barrier inventory data, traffic data, crash data, and personal injury data. The independent data collection for this research focused on roadway homogeneous segment selection and barrier-relevant crash selection. Overall, the INDOT existing databases covered the fundamental information needed for this research, and our independent data collection filled in the gaps where detailed or high resolution data were necessary.

The entire data collection and processing can be summarized as follows:

- Step 1: randomly selected homogeneous barrier and non-barrier roadway segments and recorded the roadway and roadside characteristics using Google Earth software.

- Step 2: assigned all crashes that occurred from 2003 to 2012 on those selected segments.
- Step 3: selected from all the assigned crashes, those relevant to road barriers using the crash reports and collision diagrams.
- Step 4: joined other useful information to those selected crashes and segments, such as information for the traffic, speed limit, vehicles, occupants, and injury levels.

4.2 Barrier Inventory Data

The barrier inventory data provided the location of barriers based on the linear reference system, which helped us navigate our barrier homogenous segments selection that followed. The entire barrier inventory data were composed of three separate INDOT existing databases for each type of road barriers of interest in Indiana: the concrete barrier walls, guardrails, and cable barriers. The barrier installation date was only available for cable barriers. Most of the other two types of barriers have been used for a long time and their installation dates were very hard to trace. The barrier inventory data did not include information on the barrier placement, such as the median width and the offset to the edge of the roadway. The information for the barrier installation and placement were obtained or confirmed with the help of Google Earth images, which are introduced in Section 4.3.

The inventory data for guardrails and concrete barrier walls were obtained from INDOT's Work Management System (WMS). The guardrail database contained 34,214 records and covered a total of 2,483 miles of roadway, including interstates, US highways, and state roads. The route, the side of the road, and the start and end mileposts were provided for each guardrail section. The barrier wall inventory data were arranged in a form similar to the guardrail inventory data.

The cable barrier inventory data contained 49 records with a total length of around 370 miles. Cable barriers have been placed on interstates such as I-64, I-65, I-69, I-70, I-74, I-80, and I-265, and were installed in different years with the earliest in 2006 and the latest in 2012. Cable barriers installed after year 2012 were not included.

4.3 Roadway Segment Data

Roadway segments were important to this study mainly due to two reasons: 1) they were the observations for developing our barrier-relevant crash frequency model and 2) they comprise the basic platform where crashes, vehicles, and occupants could be joined together for developing the event model and injury model which followed. For quality and resolution requirement, this study conducted independent data collection on roadway segment selection. Trained data collectors randomly selected homogeneous roadway segments using Google Earth software following the carefully designed collection procedure as shown in Appendix A. The selected segments generally represented the use of barriers in Indiana. The originally selected segments were bi-directional (including two-way traffic) with information for each direction recorded. Each bi-directional segment is then divided by the median into two separate directional segments for following analysis. All the recorded directional specific information on those directional segments forms a dataset which we call as segment dataset.

4.3.1 Segment Data Selection

The Indiana barrier inventory allowed randomly selecting roadway segments (bi-directional) with barriers from all the INDOT-administered divided roads. After the sample of segments with barriers was selected, each barrier segment was matched with a homogeneous segment with no barrier located as nearby as possible. The purpose of the pair matching was to minimize the difference between the two segments in roadway geometry, roadside hazards, traffic volume, driver population, and weather conditions. Both urban and rural interstates, U.S. highways, and state roads were included. Those bi-directional were divided into directional segments for the following analysis. The obtained sample contained a number of 1,258 paired directional segments which covered nearly 330 miles of state-administered roads. Table 4.1 illustrates the number of directional segments classified by different median and roadside scenarios.

A visual inspection of the Google Earth images was performed for both the barrier and non-barrier segments to check their longitudinal and temporal homogeneity. The beginning and end of a segment was determined in such a way that no obvious change of the cross-section and the roadside features were present along the obtained segment. The satellite and street-view Google Earth images were inspected to check if the roadway characteristics (e.g., the number of lanes, the median width, the shoulder width, etc.) and roadside characteristics (e.g., presence and type of barriers, the barrier offset, the tree density, etc.) were nearly constant throughout the segment. Then, the old Google Earth images were inspected to make sure the barriers were installed before the period of analysis and that the road did not undergo any major geometry changes (e.g., adding a lane, narrowing the shoulder, etc.). Figure 4.1 illustrates the segment selection process in Google Earth.

Table 4.1 Number of Collected Directional Segments by the Median and Roadside Scenario

Median Scenario	Roadside Scenario			
	High-hazard roadside (hazard rating 3 to 7)	Low-hazard roadside (hazard rating 1 or 2)	Guardrail	Total
Nearside Cable Barrier (offset <=30 feet)	42	35	16	93
Far-side Cable Barrier (offset>30ft)	39	37	17	93
Concrete Barrier	98	12	44	154
Guardrail	14	7	41	62
Narrow Median (width<=50ft)	41	66	69	176
Wide Median (width>50ft)	202	362	116	680
Total	436	519	303	1258

Trained observers inspected each of the 1,258 directional segments with the Google Earth images and extracted a wealth of information about the roadway and roadside hazards, including the shoulder types and widths, the median type and width, the number of lanes, the presence of horizontal curves, the presence of rumble strips, the total number of access points, and the roadside hazard rating index following the Highway Safety Manual (AASHTO, 2010) guidelines. A dataset, called the segment dataset was created to store the information. The procedure and details for extracting that information were included in the training manual for segment selection in Appendix A.

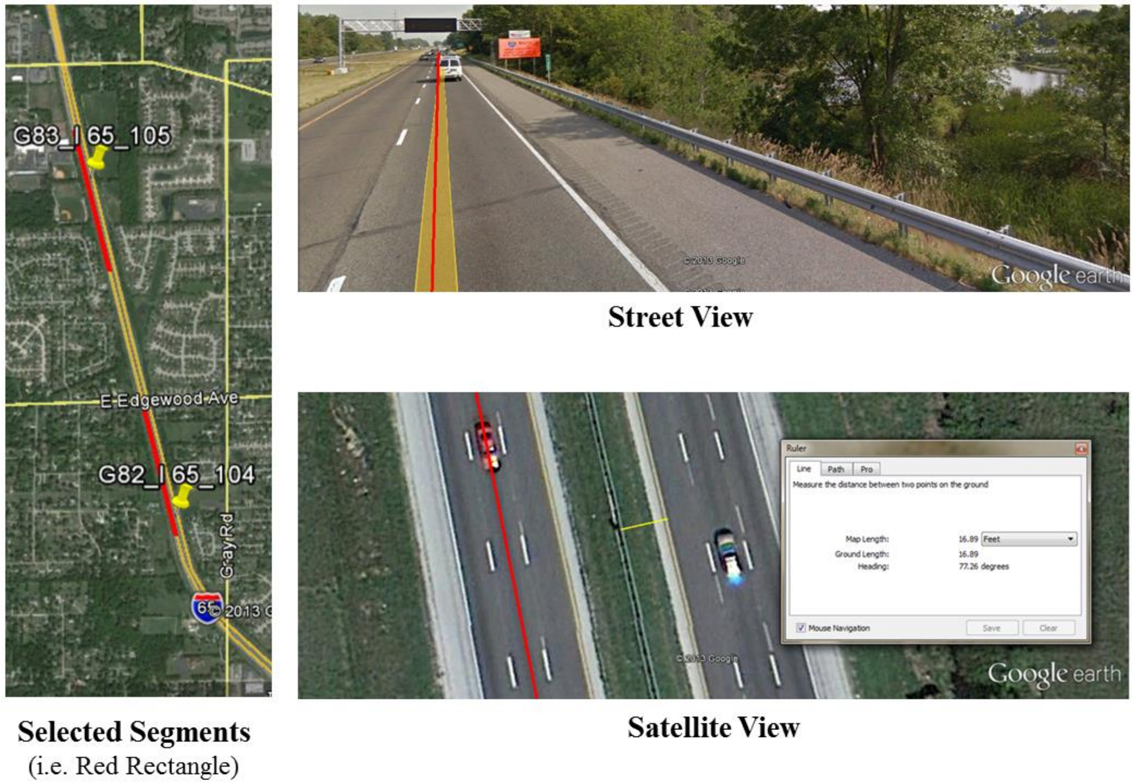


Figure 4.1Segment Selection Using Street View and Satellite View in Google Earth

4.3.2 Segment Data Summary

Summary statistics based on the selected sample of segments were analyzed to understand the barrier's use and placement. Differences in placement of median barriers can be summarized from two aspects: 1) the applicable median width and 2) how far the barrier was placed away from the edge of the roadway (i.e., barrier offset). For roadside barriers, the difference in placement was only reflected by how far they were placed away from the edge of the roadway. Most of the concrete barrier walls were placed in the center of paved medians; all cable barriers were near one side of the roadway in unpaved medians; guardrails were either in unpaved medians or on the roadside or in both locations. There is a new practice in Indiana of placing median guardrails in narrow paved medians, but this case was not included in the study due to the shortage of data.

Figure 4.2 shows the histograms of the median width for three types of collected median barrier segments. It can be seen that concrete barrier walls were used on narrow medians with median widths less than 40 feet, whereas cable barriers appeared to be consistently used on wide medians with median widths around 60 feet. The use of median guardrails was much more flexible. As Figure 4.2 shows, cable barriers overlap with guardrails on median widths that ranged from 50 feet to 70 feet while concrete barrier walls overlapped with guardrails on median widths that ranged from 16 feet to 40 feet, which indicates that guardrails could be a viable alternative for either concrete barrier walls or cable barriers on their respective applicable median.

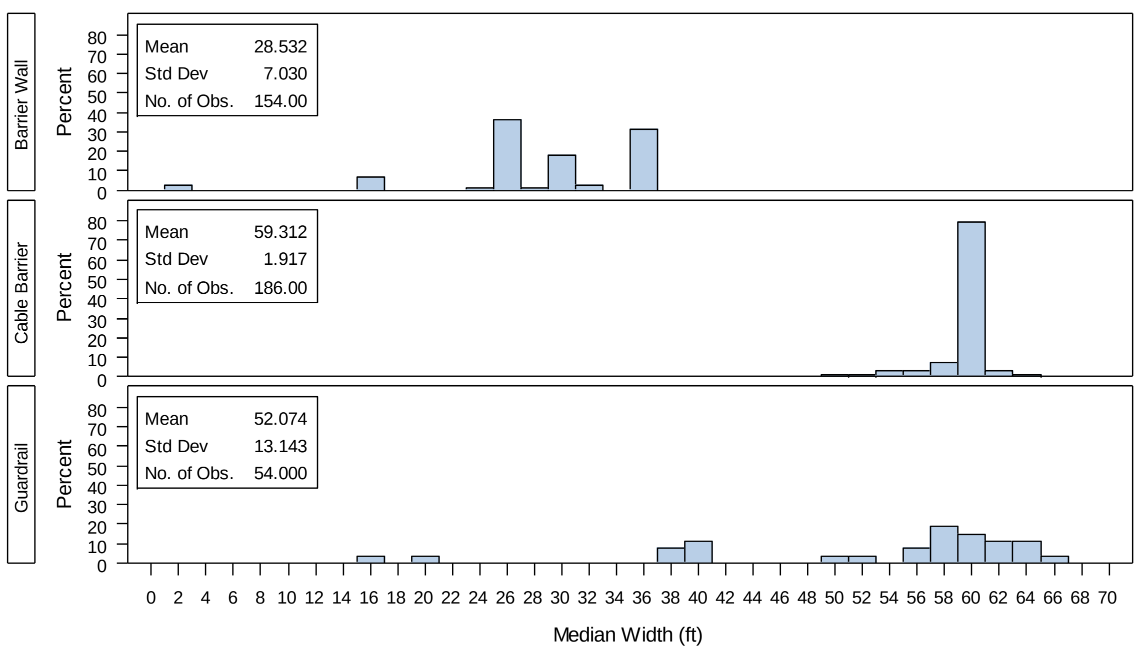


Figure 4.2 Histograms of the Median Width

Figure 4.3 shows the histograms of median barrier offsets for directional segments with different types of median barriers. It can be seen that the offsets of median concrete barrier walls were less than 20 feet, which was half of their applicable median width. For median cable barriers, the offsets distribution had two modal values (16 feet and 44 feet) that represented two typical locations of a median cable barrier in relation to the travelled way used by a vehicle involved in a crash: the nearside location and the far-side location. Median guardrail offsets had a distribution similar to median cable barriers but their offsets were more dispersed.

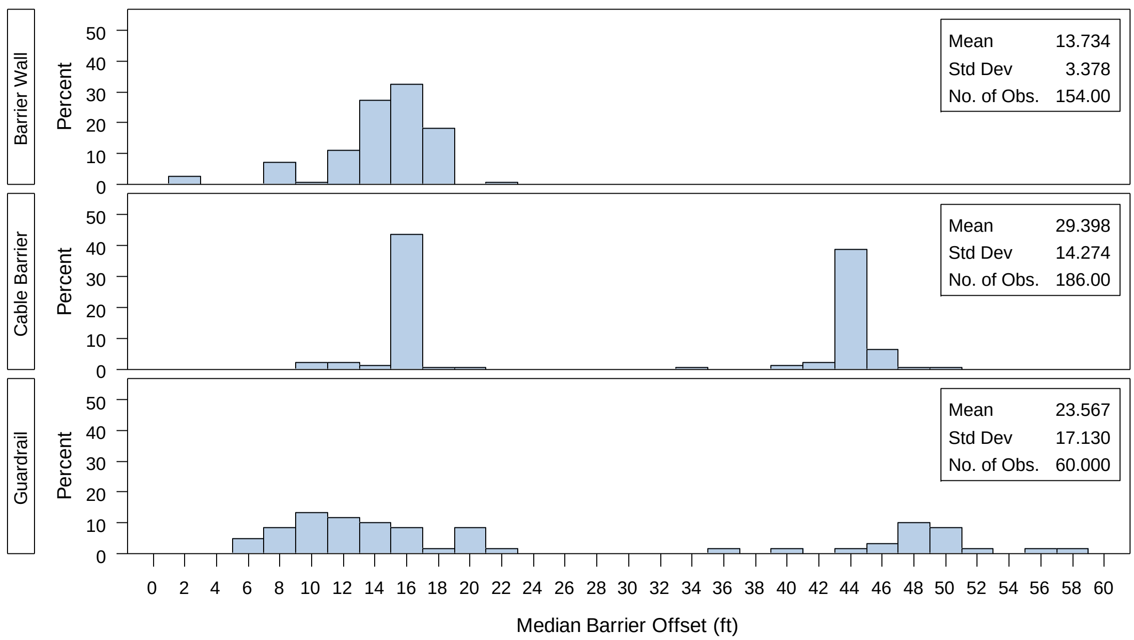


Figure 4.3 Histograms of the Median Barrier Offset

Compared to median barrier offsets, which can differ a great deal across the barrier types, the roadside barrier offsets were only available for one type of barrier (i.e., roadside guardrails); and they tended to follow a much simpler distribution such as the normal distribution shown in Figure 4.4. The values ranged from 2 feet to 18 feet, with the majority of them concentrating on values from 10 feet to 12 feet.

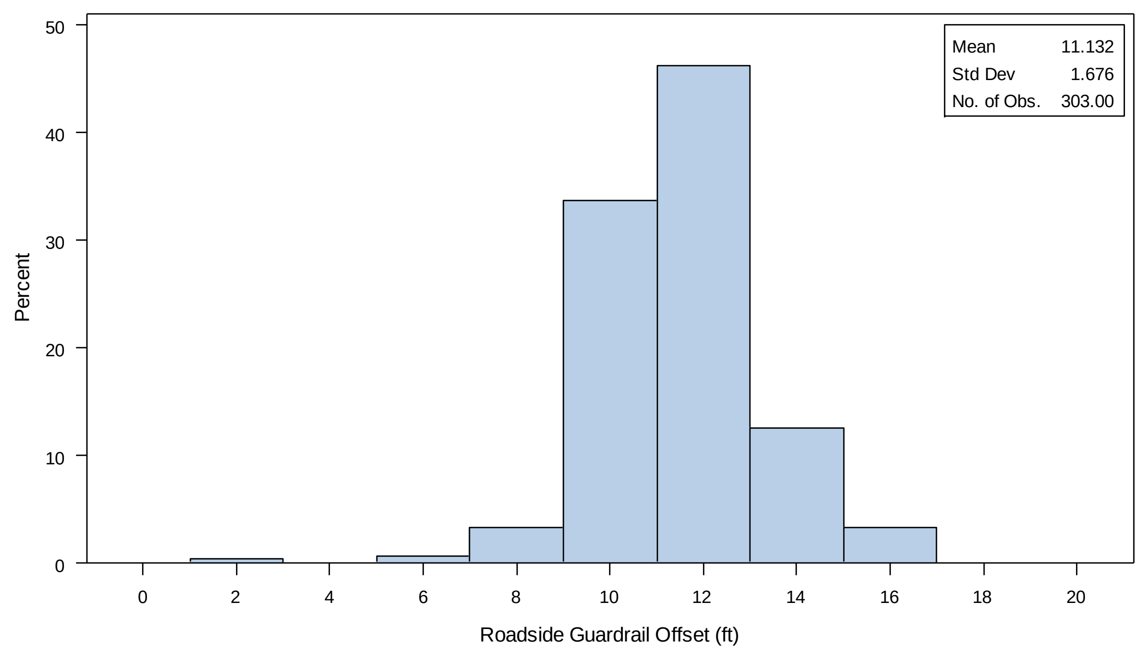


Figure 4.4 Histogram of Roadside Guardrail Offset

4.4 Crash and Traffic Safety Data

The information for the crashes that occurred on the selected segments was important for evaluating the in-service performance of barriers. It is important to note, however, that not all the geo-located crashes were relevant to the evaluation. Even for a barrier-relevant crash, some vehicles might be irrelevant. The subsections below discuss how barrier-relevant crashes and vehicles are identified. The data consistency check also will be discussed.

4.4.1 All Assigned Crashes

Based on the homogeneous segments mentioned above, a total of 20,370 crashes from 2003 to 2012 were assigned based on their geo-referencing information. Other useful information available in the existing INDOT crash database was also joined. The crash-related dataset included the following four datasets:

- The crash dataset (20,370 records): crash-level information such as crash date, crash location, crash type, number of vehicles, roadway surface conditions, etc.
- The vehicle dataset (29,402 records): It includes the involved vehicles as well as other units such as trailers, bicycles, etc. Vehicle level information was recorded such as the occupancy, vehicle type, travelling direction, road type, sequence of events, etc.
- The individual dataset (63,150 records): It includes the person-level information such as the person type (e.g., driver, injured, pedestrian, etc.) and address.
- The injury dataset (29,726 records): It includes the age, gender, injury level (KABCO scale), etc. for the driver and injured occupants (person-level).

4.4.2 Barrier-relevant Crash Selection

Barrier-relevant crashes have been defined in Section 3.3. Three steps were conducted to select the barrier-relevant crashes. They are:

- Select candidate crashes using information in available databases
- Remove crashes that occurred on or before the installation year of cable barriers
- Clean crashes and extract information using police narratives and collision diagrams

The first step selected candidate crashes by taking advantage of the information available in the INDOT existing crash-related databases. Two sources of information were used: the type of crash ("mannercollcde" in the crash dataset) and the sequence of events (“eventcollwithcde”, “eventcollwithcde2”, “eventcollwithcde3” and “eventcollwithcde4” in the vehicle dataset). The candidate crashes were those with type of crash entry codes 02, 04, 05, 06, 12, and 13 (see below for the entry coding) and with any of the four event entry codes 01, 15, 20, 30, 32, 35, 37, 38, 39, 40, 41, 42, 43, 45, 47, 48, 49, 50, 51, 52, 53, 55, 59, 60, 61, or 62 (entries 53 to 62 are only available for crashes that occurred in 2011 or later). Below are the available entries for those two variables. Bolded entries are those used to select candidate crashes.

For the type of crash:

- 01 - Rear end
- **02 - Head on**
- 03 - Rear to rear
- **04 - Same direction sideswipe**
- **05 - Opposite direction sideswipe**
- **06 - Ran off road**
- 07 - Right angle
- 08 - Left turn
- 09 - Right turn
- 10 - Left/right turn
- 11 - Backing crash
- **12 - Other - explain in narrative**
- **13 - Non-collision**

For the sequence of events,

- **01 - Another Motor Vehicle**
- 02 - Pedestrian
- 03 - Bicycle

- 04 - Railway Vehicle/Train/Engine
- 05 - Deer
- 06 - Animal Other Than Deer
- 07 - Animal Drawn Vehicle
- **15 - Overturn/Rollover**
- 16 - Fire/Explosion
- 17 - Immersion
- 18 - Jackknife
- 19 - Cargo/Equipment Shift Or Loss
- **20 - Off Roadway**
- 21 - Fell From Vehicle (Non Collision)
- **30 - Impact Attenuator/Crash Cushion**
- 31 - Bridge Overhead Structure
- **32 - Bridge Pier Or Abutment**
- 33 - Bridge Parapet End
- 34 - Bridge Rail
- **35 - Guardrail Face**
- 36 - Guardrail End
- **37 - Median Barrier**
- **38 - Highway Traffic Sign Post**
- **39 - Overhead Sign Post**
- **40 - Light/Luminaire Support**
- **41 - Utility Pole**
- **42 - Other Post/Pole Or Support**
- **43 - Wall/Building/Tunnel**
- 44 - Work Zone Maintenance Equipment
- **45 - Embankment**
- 46 - Curb
- **47 - Ditch**

- **48 - Culvert**
- **49 - Fence**
- **50 - Mailbox**
- **51 - Tree**
- **52 - Other - Explain In Narrative**
- **53 - Crossing Center Line/Median**
- 54 - Equipment/Mechanical Failure
- **55 - Downhill Runaway**
- 56 - Separation Of Units
- 57 - Thrown Or Falling Object
- 58 - Parked Motor Vehicle
- **59 - Ran Off Roadway**
- **60 - Cable Barrier**
- **61 - Concrete Traffic Barrier**
- **62 - Other Traffic Barrier**

The second crash selection step removed the crashes that occurred on or before the installation year of cable barriers, given that Indiana recently began installing cable barriers.

Although the first and second steps removed the crashes which were irrelevant to this study, it was still uncertain if the remaining candidate crashes were barrier-relevant crashes due to the outdated entries for the sequence of events in earlier years and the inconsistency of coding those events among different police officers. For example, the entry for cable barrier had not been an available entry until November 2011. Police might code collided cable barriers as fence, impact attenuator, or others before November 2011.

Even for crashes occurred in the same manner, different police officers might code them differently.

Other than the necessity of improving the selection accuracy of barrier-relevant crashes, there was more work that was needed to extract the detailed characteristics of the errant vehicles and to verify crash locations, which the current existing INDOT databases did not fully cover. The questions that remain to be addressed include:

- Whether a vehicle left the roadway at any point?
- Whether a vehicle went to the left or right after it left the roadway?
- Did the vehicle cross the median?
- What type of event did the vehicle encounter after it left the roadway?
- What was the vehicle's status after its hazardous event?
- Where did the vehicle finally come to a rest after its hazardous event?

Additional questions on the barrier collision crashes of interest also needed to be addressed:

- What type of barrier did the vehicle strike?
- Was the collided barrier a median barrier or roadside barrier?

Thus, a third crash selection step was conducted with the aim to improve barrier-relevant crash selection and information extraction of vehicles' ROR characteristics. This step was supported by independent data collection on the crash-by-crash interpretation of police narratives and collision diagrams documented in electronic police crash reports. Crash reports were accessed from the Automated Reporting Information Exchange System (ARIES), and each report was interpreted by trained data collectors. The ROR related variables of interest were recorded for each involved vehicle in a carefully designed spreadsheet. Figures 4.5 and 4.6 are the examples of the crash diagram and narration respectively.

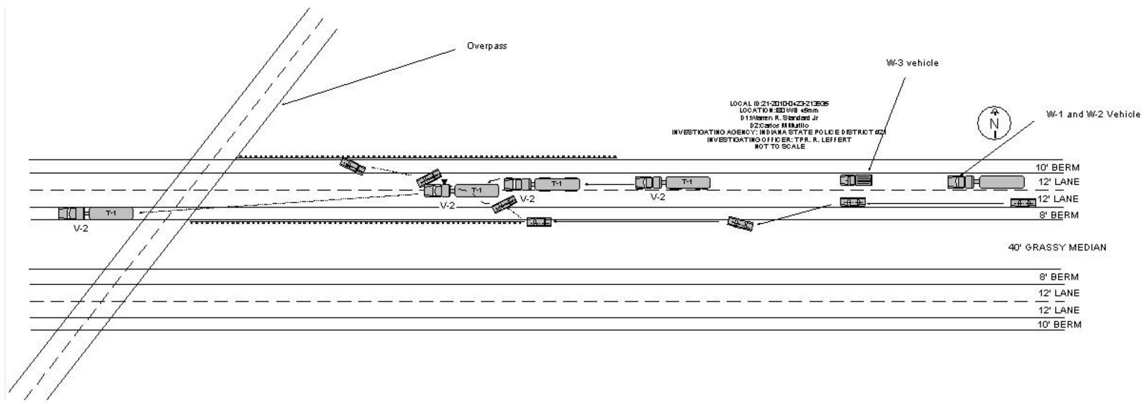


Figure 4.5 An Example of Crash Diagram

Narrative

Vehicle 1 was traveling south on Interstate 65 at the 28 mile marker in the right lane.
Witness 1 was traveling north on Interstate 65 at the 28 mile marker in the left lane.
Vehicle 1 was traveling south on Interstate 65 at the 28 mile marker in the right lane when he ran off the road onto the right shoulder. Vehicle 1 struck the guard rail face with it's right side. Vehicle 1 then struck the bride support for the County Road 150 overpass with it's right side. Vehicle 1 then veered across Interstate 65 south, entered the median, crossed onto Interstate 65 north, and came to rest in the right lane and shoulder of Interstate 65 north. The damage to Vehicle 1 was caused by the impact to the guard rail and bridge support. Vehicle 1 lost most of the right side of the tractor and ripped opened the trailer causing the load to eject throughout the median and onto Interstate 65 north.
Witness 1 was traveling north on Interstate 65 at the 28 mile marker in the left lane when he advised he saw Vehicle 1 coming across the median toward him. Witness 1 was able to pull his tractor/trailer into the median to avoid being struck. Witness 1 had to have his vehicles wenched out of the median due to the muddy conditions.
Driver 1 advised he was traveling south on Interstate 65 at the 28 mile marker in the right lane when he took a drink of coffee. Driver 1 advised he aspirated the coffee and began to choke. Driver 1 advised he was coughing frantically trying to catch his breath. Driver 1 advised he tried to ease Vehicle 1 onto the shoulder until he regained himself. Driver 1 advised he came to on the opposite side of Interstate 65 and did not remember striking anything or crossing the median. Driver 1 further advised he had falsified his log book. Driver 1 relinquished his log book for a level III inspection. The log page for March 30, 2010 showed him in Whiteland, Indiana at 2015 hours. This crash occurred at 2002 hours in Scottsburg, Indiana. Driver 1 advised he went ahead and pre-planned his trip on his log page. Driver 1 advised he drew a ten hour break but only took eight hours. Driver 1 had a total of fifteen hours of drive time at the time of the crash. Driver 1 did advised me of the log violation before I began the inspection.

Figure 4.6 An Example of Crash Narration

Moreover, the geometric characteristics (i.e., the presence of a junction and a horizontal curve and the number of lanes) at the crash site were also extracted from crash diagrams. These crash site geometry features were useful in verifying if crashes were correctly assigned. See Appendix B for a list of the variables that trained data collectors used to characterize the vehicles' ROR details and crash site geometry.

After the third step, barrier-relevant crashes and vehicles were finally identified. The corresponding recorded information was stored in a dataset called the ROR dataset. Ann occupant-level dataset called the barrier-relevant occupant dataset that was composed of information about the barrier-relevant occupants. All the information from the INDOT existing databases (individual dataset, injury dataset, vehicle dataset, and crash dataset) and our independent data collection (ROR characteristics, crash site characteristics, and segments' roadway and roadside characteristics) were joined to each occupant.

4.4.3 Data Consistency Check

The aforementioned barrier-relevant occupant dataset contained a wealth of information from different data sources. Some information was available from multiple data sources. The data consistency check took advantage of the information redundancy and identified records with their shared information inconsistently recorded among different data sources. Inconsistencies in the shared information were indications of potential data reporting problems or crash location assignment precision problems. Crashes with inconsistencies in the important characteristics were removed from the analysis. Below is the selected information used to conduct the consistency check:

Number of lanes

Information on the number of lanes for a given crash was recorded by three datasets: the vehicle dataset, the segment dataset, and the ROR dataset. Inconsistent descriptions of the number of lanes among the three datasets could be due to the operator's incorrect counting, road construction work, and crash location reporting errors. Crashes with inconsistent descriptions of the number of lanes were removed given that they were very likely inaccurately assigned to the segment.

Presence of intersection

Since all of the crashes were originally selected based on homogeneous road segments, all the crashes in this study were not to have any indication of the presence of any type of intersection. Information on the presence of intersection was available in the crash dataset and the ROR dataset. The inconsistency was most likely due to crash location reporting errors. Thus, such crashes were removed if the presence of an intersection was indicated in either the crash dataset or the ROR dataset.

Presence and type of barriers

Three datasets (vehicle dataset, segment dataset, and ROR dataset) contained information on the barrier presence and barrier type. Barrier information in the vehicle dataset was overridden by the information in the ROR dataset since those two datasets followed the same entry coding format, but the latter used the most up-to-date coding entries for barriers with higher resolution and consistency. Inconsistencies in the barrier presence and the barrier type between the ROR dataset and the segment dataset most likely indicated the presence of crash location reporting errors. Thus, the inconsistent records were removed from the analysis.

Presence of horizontal curve

Three datasets (crash dataset, segment dataset, and ROR dataset) described the presence of horizontal curve. Note that the horizontal curve was allowed in our homogeneous segment selection. Inconsistent descriptions of the presence of horizontal curves among three different datasets may have been due to different curve judgment criteria provided by operators or crash location reporting errors. Investigation of a sample group of horizontal curve inconsistent crashes indicated the former reason dominated (i.e., whether or not a given segment was deemed as horizontally-curved varied person by person). Therefore, horizontal curve inconsistent crashes were not removed, but their use in the analysis was done with caution.

4.4.4 Crash Data Summary

After the data reduction and cleaning, a number of 2,049 barrier-relevant crashes (2,124 vehicles and 3,299 occupants) from 2003 to 2012 were finally selected. They occurred on a number of 732 out of 1,258 homogeneous roadway segments.

A number of 62 near-side cable barrier collision crashes (96 occupants), 42 far-side cable barrier collision crashes (55 occupants), 382 median concrete barrier collision crashes (561 occupants), 69 median guardrail collision crashes (117 occupants) and 158 roadside guardrail collision crashes (241 occupants) were included.

4.5 Traffic and Speed Limit Data

The information on the AADT and speed limit was provided by the Center for Road Safety, Purdue University and was linked to each selected segment using ArcGIS software. The AADT for different years was calculated based on the adjustment factors suggested by INDOT.

4.6 Cost per Injury Data

The safety benefits of using road barriers are measured in terms of the saved crash costs. The saved crash costs due to barriers on a segment were calculated as the total crash costs without using barriers minus the total crash costs using barriers. The total crash costs were calculated as the summation of the costs for each occupant. Table 4.2 is the average comprehensive cost per injured person by injury severity according to the National Safety Council (2011).

Table 4.2 Average Comprehensive Cost per Injured Person by Injury Severity (National Safety Council, 2011)

Injury Level	Average Comprehensive Cost (2011)
Death (K)	$4,459,000
Incapacitating injury (A)	$225,100
Non-incapacitating injury (B)	$57,400
Possible injury (C)	$27,200
No injury (O)	$2,400

4.7 Chapter Summary

The data needed for this study included: roadway segments, crashes, vehicles, occupants, and other relevant data such as traffic volumes, speed limits, etc. Most of the data were obtained from the INDOT existing databases and from independent data collection. Trained data collectors used Google Earth images to select homogenous roadway segments. The electronic crash reports assessed from the ARIES system were used to clean up the crash data and extract the details of the ROR behavior of vehicles. Data with shared information inconsistently recorded by different sources were either removed or used with caution.

After data collection and reduction, a number of 1,258 barrier and non-barrier directional segments were selected. They covered nearly 330 miles of state-administered divided roads. The selected segments allowed selecting a number of 2,049 barrier-relevant crashes (2,124 vehicles and 3,299 occupants) from 2003 to 2012. The barrier-relevant crashes were crashes where the outcomes were affected or might have been affected by a barrier had the barrier been installed. The selected barrier-relevant crashes occurred on a number of 732 out of 1,258 homogeneous roadway segments.

CHAPTER 5. FREQUENCY MODEL

This chapter discusses the crash frequency analysis conducted in this study, which includes the statistical modelling framework, the variable processing, the summary statistics of the data, and the modelling results. The crash frequency analysis is a component of the overall in-service safety evaluation of barriers.

5.1 Introduction

The objective of the barrier crash frequency analysis was to develop a statistical model for 1) estimating the change in barrier-relevant crash frequency due to the installation of different barriers and 2) predicting the barrier-relevant crash frequency for different median and roadside scenarios (including barrier and non-barrier scenarios).

An analysis of the change in crash frequency due to barriers was important and necessary in this study because many states have observed that the total number of crashes have increased since the installation of median barriers, although those crashes have tended to be less severe. The benefit of barriers in reducing the crash injury level may offset its drawback of increased crash frequency. Crash injury analysis without accounting for the changes in crash frequency could over-estimate the performance of barriers.

The crash type primarily impacted by barriers is the ROR crash because barriers reduce the width of the recovery area and eliminate the possibility of missing the roadside hazard. Thus, the risk of hitting a barrier tends to increase as well as the frequency of reported ROR crashes. As explained in Section 3.3, not all ROR crashes are barrier-relevant, but most of them tend to be so. It also should be noted that crashes where the crash type is not designated as "run-off-roadway," may be barrier-relevant. For example, the crash type of cross-median head-on is normally designated as "head-on" according to the standard practice of the Indiana crash database. The crashes of interest for this study were barrier-relevant crashes.

Prediction of barrier-relevant crashes for different median and roadside scenarios was a major motivation for the study in this chapter. For example, for a given non-barrier road segment with certain road characteristics, the proposed model could be used to predict the number of barrier-relevant crashes, assuming the presence of a certain type of barrier with a certain offset value. This prediction process could be repeated for all possible viable median and roadside treatment scenarios (i.e., combinations of certain median barrier types and roadside barrier types and their respective offsets) under its given road and roadside characteristics. Finally the crash frequency numbers for each treatment scenario could be determined, compared, and prepared for further analysis.

It is important to note that the crash frequency analysis does not tell the whole story of the effectiveness of barriers but rather is just the first step toward a full assessment of the overall performance of barriers. How barriers change crash events and, subsequently, the entire injury level distribution will be addressed in Chapters 6, 7, and 8.

5.2 Modelling Framework

5.2.1 Functional Form and Variables

A negative binomial regression model was developed to estimate the barrier-relevant crash frequency based on the collected segment data and crash data from 2008 to 2012. The negative binomial models frequently have been used to model crash frequency due to their simpler variance function and closed form likelihood function. Although many alternatives are available in frequency modelling as mentioned in Section 2.3.1, the results of some models may not be easily transferable to other datasets (Lord and Mannering, 2010). Given that this study not only focused on the statistical inference but also emphasized the implementation of the developed models in prediction, a traditional negative binomial regression model was deemed adequate to meet the research objective.

The functional form of the developed negative binomial model in this study is shown as below:

$$C_i = N_i \times AADT_i^{\beta_1} \times SegL_i^{\beta_2} \times \exp\{\boldsymbol{\beta}\mathbf{X_i}\} \tag{5.1}$$

where,

C_i	= mean number of barrier-relevant crashes during the analysis period for directional segment i;
N_i	= number of years during the analysis period for directional segment i;
$AADT_i$	= directional annual average daily traffic (AADT) in veh/day for directional segment i;
$SegL_i$	= segment length in miles for directional segment i;
β_1, β_2, and $\boldsymbol{\beta}$	= vector of estimated coefficients;
$\mathbf{X_i}$	= vector of explanatory variables such as the roadway functional class, speed limit, presence of different types of barriers for directional segment i.

The response variable was the number of barrier-relevant crashes for a given homogeneous segment over its analysis period. It should be noted that each analyzed segment was a directional segment, and all the information relevant to the segment was direction-specific. For example, the traffic volume variable AADT linked to each analyzed segment was calculated as the half of the AADT for the corresponding bi-directional segment. Whether the horizontal curve was to the left or to the right of the roadways refers to the travelling direction of the vehicles driving on the directional segment.

The number of years of the analysis period was set as the offset variable or exposure variable. In this study, the analysis period of a segment depended on the barrier type. For segments with barriers installed before 2008 and their matched non-barrier segments, which was the case for segments with concrete barriers, guardrails, and a small portion of cable barriers, the analysis period was 2008 to 2012. For segments with barriers installed on or after year 2008, which was the case for the majority of cable barriers, the analysis period was from the year after installation through 2012. Although we extracted 10 years of data (2003 to 2012) for most of the segments, the frequency analysis only focused on the most recent five years because the accuracy of the crash assignment was higher in the later records.

The explanatory variables that were important in this study included the log of the AADT averaged over the analysis period, the log of the adjusted segment length (see more details in Section 5.2.3), the generic variables representing the roadway functional class and speed limit combined, the median and roadside barrier variables, and the horizontal curve variables (tangent, curved to the left or to the right).

Due to the high correlation between the roadway functional class and the speed limit, treating those two variables separately and putting them in the model could lead to a potential problem of multicollinearity and misleadingly increase the standard errors of the coefficients. In this study, we instead considered those two variables together and formed three mutually exclusive categories: 1) freeway with speed limit 65 mph or higher, 2) freeway with speed limit 60 mph or lower, and 3) non-freeway. The non-freeway category was set as the reference category. The coefficients for the other two categories reflected how much they differed from the reference category in terms of the crash frequency number.

The most important variables were the barriers, and the focus was to compare the use of barriers with no barrier usage as well as the differences across different barrier types and offsets. The barriers were modeled under the context of different median and roadside scenarios. See Section 3.2 for the original division of those scenarios. Generally speaking, the median or roadside environment was divided into two alternatives: barrier and non-barrier. For the barrier alternative, it was further divided by the barrier type and offset to the edge of the travelled way. For the non-barrier alternative, it was further classified by the median width (for the median) or the roadside hazard rating level (for the roadside). It should be noted that the scenarios that produced similar modelling effects were combined in the final results.

5.2.2 Summary of Statistics

Tables 5.1 and 5.2 provide the summary of statistics for the continuous and categorical variables of interest respectively.

Table 5.1 Summary of Statistics of the Continuous Variables in Crash Frequency Model (Segment Level)

Variable	Number of observations	Mean	Standard deviation	Minimum	Maximum
Number of barrier-relevant crashes that occurred from 2008 to 2012	1258	1.275	1.933	0.000	14.000
Average daily traffic (vehicle/day)	1258	15,439	9,731	1,215	77,801
Segment length (mile)	1258	0.261	0.179	0.057	0.965
Median width (feet)	1258	57.59	32.35	1.00	420.00
Inside shoulder width (feet)	1258	6.667	3.583	0.000	21.000
Outside shoulder width (feet)	1258	10.804	1.504	0.000	22.000

Table 5.2 Summary of Statistics of the Categorical Variables in Crash Frequency Model (Segment Level)

Variables	Categories	Count	Percentage (%)
Functional class and speed limit	Freeway with a speed limit 65mph or higher	940	74.72
	Freeway with a speed limit 60mph or lower	80	6.36
	Non-freeway	238	18.92
Horizontal curve	Left curve	45	3.58
	Right curve	45	3.58
	Tangent	1,168	92.84
Urban area Indicator	Urban	342	27.19
	Rural	916	72.81
Median scenario	Nearside Cable Barrier (offset <=30 feet)	93	7.39
	Far-side Cable Barrier (offset>30ft)	93	7.39
	Concrete Barrier	154	12.24
	Guardrail	62	4.93
	Narrow Median (width<=50ft)	176	13.99
	Wide Median (width>50ft)	680	54.05
Roadside scenario	High-hazard roadside (hazard rating 3 to 7)	436	34.66
	Low-hazard roadside (hazard rating 1 or 2)	519	41.26
	Guardrail	303	24.09
Number of Lanes	Two lanes	1,147	91.18
	Three lanes	96	7.63
	Four lanes	8	0.64
	Five Lanes	7	0.56

5.2.3 Adjustment for the Crash Migration Problem

In this study, the crash migration problem indicates that a crash that occurred outside of a selected segment was incorrectly assigned to this segment due to the poor accuracy of the location information on the crash record. This problem was analyzed by this study.

The variable segment length measured in Google Earth could have been handled either as an explanatory variable or as an offset variable (exposure variable). This study first included the segment length in the model as an explanatory variable and found that the estimated coefficient for the log of the segment length was less than 1 and not even close, which indicated that the variable segment length did not quite perform like an offset variable and was not linearly associated with the number of barrier-relevant crashes. More specifically, it suggested that the rate of increase in the number of barrier-relevant crashes was much smaller than that in the segment length.

In fact, the non-linear relationship was related to the accuracy issue in police reporting of crash locations. In general, the process of assigning crashes consists of the police officer taking the nearest milepost or the nearest intersection as the reference point and then estimating the distance of the actual crash location to the reference point. As a result, the larger the actual distance was, the lower the accuracy of the estimated distance. There also were some cases where the police officer did not provide the estimated distance or assumed it to be zero. The consequences of those two facts leads to the phenomenon of the data showing that locations near a physical milepost have more reported crashes than those farther away. In other words, the reported crash locations from the data tend to concentrate on the physical milepost.

However, the actual crash location should have nothing to do with where the physical milepost is located, which brings up the need for adjustment of the crash location migration. For segment selection in this study, the data collectors always started from a physical integer milepost and all the selected homogenous segments contained this milepost spot. All of the segments had a tendency to include "extra" crashes that actually occurred on nearby segments with no mileposts. This situation could have led to a bias in the frequency analysis since crashes on nearby segments also were counted in the response variable (i.e., the number of barrier-relevant crashes on a homogenous segment of interest). Generally, the shorter the homogeneous segment was, the lower the accuracy of the response variable. Segments with lengths larger than one mile were basically not affected.

To address the problem, we applied an adjustment of the exposure related to the segment length. Assume for a homogenous segment with length L which includes a physical milepost that the actual crash locations are uniformly distributed with its density d. So Ld is the number of crashes that actually occurred on that segment. The "extra" crashes are calculated as $k(1-L)d$, with k indicating the proportion of the crashes that actually occurred on the nearby segment with the length $(1-L)$ but were incorrectly assigned to the milepost of the segment of interest segment. So the crash count directly obtained from the data is $Ld + k(1-L)d = [L + k(1-L)]d = L'd$, with $L' = L + k(1-L)$. L' is the adjusted segment length, which can be understood as the actual length of the segment plus an equivalent extra length to account for the crash migration.

The adjusted segment length then was used to estimate the frequency model. The value of k was determined such that the estimated coefficient for the log of the adjusted segment length was reasonably close to 1, which made the adjusted segment length perform as an exposure variable. We looped through different values of k from 0 to 1 with 0.02 as the increment. The results under several selected k values are shown in Table 5.3. It can be seen that other than the coefficient for the adjusted segment length, the difference in the coefficients for the other variables and the goodness-of-fit statistics across different k values were small. In the end, we selected $k = 0.28$ to adjust the segment length and then estimated the frequency model based on this adjustment.

Table 5.3 Parameter Estimates and Goodness-of-Fit Statistics under Different k Values

Variables	Parameter Estimates							
	k=0	k=0.10	k=0.20	k=0.26	k=0.28	k=0.30	k=0.40	k=0.90
Intercept	-8.0937	-8.0386	-7.9915	-7.9673	-7.9597	-7.9524	-7.9191	-7.7997
Log of directional AADT in vehicles per day	0.5993	0.6038	0.6053	0.6058	0.6060	0.6061	0.6066	0.6080
Log of adjusted segment length in miles	0.3884	0.5863	0.8030	0.9535	1.0083	1.0658	1.4051	12.7516
Freeway with speed limit 65 mph or higher	1.6632	1.6600	1.6609	1.6619	1.6622	1.6626	1.6644	1.6723
Freeway with speed limit 60 mph or lower	0.9531	0.9430	0.9408	0.9405	0.9404	0.9405	0.9409	0.9456
Non-freeway	Reference							
Median concrete barrier	0.9696	0.9801	0.9840	0.9852	0.9854	0.9857	0.9865	0.9865
Median guardrail (face)	0.6547	0.6151	0.5977	0.5908	0.5888	0.5870	0.5794	0.5585
Median cable barrier	0.2940	0.2819	0.2758	0.2732	0.2724	0.2717	0.2687	0.2605
No Median Barrier	Reference							
Right horizontal curve on a median barrier segment	0.9355	0.9447	0.9452	0.9446	0.9443	0.9440	0.9423	0.9335
No right horizontal curve on a median barrier segment	Reference							
Dispersion	0.3786	0.3776	0.3771	0.3769	0.3768	0.3768	0.3767	0.3772
Log likelihood	-1661.0	-1661.3	-1661.5	-1661.6	-1661.7	-1661.7	-1661.9	-1662.8
AIC	3341.9	3342.5	3343.0	3343.3	3343.4	3343.5	3343.9	3345.6
No. of observations	1258	1258	1258	1258	1258	1258	1258	1258

5.3 Modelling Results

The modelling results for the crash frequency analysis are shown in Table 5.4. The coefficient for the variable log of the AADT was smaller than 1 but was reasonably close. When the coefficient was close to 1, the rate of increase in the barrier-relevant crash frequency was somewhat equal to the rate of the increase in the AADT, which reflected its attribute as an exposure variable. Nonetheless, when the coefficient was smaller than 1, it was suggested that the former increase rate was less than the latter, which could be explained by the fact that, for an individual driver, an increase in the traffic volume on a segment could make the driver more focused and thus less likely to leave the roadway.

Table 5.4 Estimation Results of the Frequency Model (Negative Binomial Regression)

Variables	Parameter Estimate	Standard Error	Wald Chi-Square	P-value
Intercept	-7.9597	0.7901	101.50	<.0001
Log of directional AADT in vehicles per day	0.6060	0.0846	51.35	<.0001
Log of adjusted segment length in miles	1.0083	0.1365	54.60	<.0001
Freeway with speed limit 65mph or higher	1.6622	0.1554	114.40	<.0001
Freeway with speed limit 60mph or lower	0.9404	0.2042	21.21	<.0001
Non-freeway	Reference			
Median concrete barrier	0.9854	0.1042	89.49	<.0001
Median guardrail (face)	0.5888	0.1401	17.66	<.0001
Median cable barrier	0.2724	0.1091	6.24	0.0125
No median barrier	Reference			
Right horizontal curve on a median barrier segment	0.9443	0.4859	3.78	0.0520
No right horizontal curve on a median barrier segment	Reference			
Dispersion	0.3768	0.0520		
Log likelihood	-1,661.7			
AIC	3,343.4			
Number of observations	1,258			

As the modelling results indicate, a freeway with a higher speed limit experienced the highest expected barrier-relevant crash frequency, which was exp(1.6622)=5.27 times that of a non-freeway. The crash frequency was 2.56 times that of a freeway with a lower speed limit. Those comparison results can be explained by two known facts: 1) drivers are more likely to lose control of a vehicle under higher speeds and 2) drivers are more likely to drive when fatigued on a freeway compared to a non-freeway.

In the modelling results for barriers, six original median scenarios were combined into four categories: 1) median concrete barrier wall, 2) median guardrail, 3) median cable barrier, and 4) median with no barrier installed. The median with no barriers installed was set as the reference category. No statistical difference was found across the three original roadside scenarios so the roadside scenarios, such as guardrail, were not included in the final modelling results.

The results show that all the three types of median barriers increased the barrier-relevant crash frequency compared to a median with no barriers. Median barrier walls were associated with the largest increase, followed by median guardrails, and median cable barrier exhibited the smallest increase. The number of barrier-relevant crashes on a segment with a median concrete barrier wall was 2.68 times that of a segment with no median barrier. For a segment with median cable barriers installed, the crash frequency was 1.31 times that of a segment with no median barrier. The difference across the three types of median barriers could be explained by the relative likelihood of a crash being reported when a vehicle strikes them. In barrier wall collisions, drivers were more likely to be injured due to the high structural rigidity of barrier walls, and thus more crashes were likely to be reported. Cable barrier collisions were more likely go unreported due to the more forgiving design of cable barriers.

For median cable barriers, another interesting finding is that the barrier relevant crash frequency is increased by 1.57 times when there is coexistence (i.e., interaction effects) between a cable barrier and a horizontal curve to the right. This reflects the fact that errant vehicles from a segment with a right horizontal curve would run off road to the left more often following the momentum and collide with a cable barrier in the median if there is one.

However, the interaction effects between the presence of barriers and horizontal curves were not significant for the other two types of median barriers. Moreover, the horizontal curve itself (i.e., main effects) was not significant, nor was the coexistence of a roadside barrier and curve to the left. Why only the combination of a cable barrier and a horizontal curve to the right was significant could be due to winter weather because snow accumulation and a cable barrier could trap the vehicle and make it difficult to leave the scene, given that cable barriers are used in unpaved wide medians where snow accumulation is more common.

5.4 Discussion

Some road characteristic variables were also available in this study but were not included in the final model due to their high correlation with the included variables. For example, the number of lanes is not only highly correlated with AADT, but also depends a lot on the median barrier type. That is, segments with median barrier walls are mainly associated with at least three lanes whereas those with cable barriers normally only have two lanes. Another example is the left shoulder width, which is generally larger than 12 feet when the median is treated with a barrier wall but a different width when the median is treated with other types of barriers or no barriers. Imposing those highly correlated variables on a model can cause the multicollinearity problem, which can over-estimate the standard errors of those related variables, making them appear less significant than they actually are.

In this study, the roadside characteristics were not found to significantly affect the barrier-relevant crash frequency, possibly for the following two reasons. First, homogenous segments with a roadside guardrail installed tend to be short in length. Compared to median barriers, which tend to be continuously present for a longer roadway section, the placement of roadside guardrails depends more on the site characteristics, and they often exist in a shorter and more intermittent way. As mentioned before, shorter segments tend to be more affected by the crash location migration problem. Thus, it was possible that the low accuracy in the crash frequency of short segments would not support isolating the effect of roadside guardrails from the statistical modelling. Second, roadside environments are generally more hazardous than median environments, meaning that it would be difficult for roadside errant vehicles to return to the roadway and go unreported as is the case with median errant vehicles, particularly when there is a ditch nearby along the roadside. Therefore, it was shown that the barrier-relevant crash frequency on a non-barrier installed roadside was not significantly lower than that of a roadside with a barrier installed.

5.5 Chapter Summary

The study in this chapter investigated factors influencing the barrier-relevant crash frequency. A negative binomial regression model was developed based on the number of the barrier relevant crashes that occurred on a number of 1,258 directional divided roadway segments from 2008 to 2012. For segments with cable barriers installed on or after 2008, only the crashes that occurred after the installation year were counted. With the estimated coefficients, the developed model could be used to predict barrier-relevant crash frequency under different median and roadside scenarios.

All three types of median barriers were found to increase the barrier-relevant crash frequency compared to a median with no barriers. Median concrete barrier walls increased the frequency most, followed by median guardrails and median cable barriers. The coexistence of median cable barriers and horizontal curves to the right also increased the crash frequency. Roadside guardrails were not found to significantly increase the frequency. As expected, increases in AADT increased the frequency. The rate of the increase in frequency, however, was smaller than for the AADT. The non-freeway segments tended to have a lower crash frequency than freeway segments, of which those with lower speed limits tended to have smaller crash frequency than those with higher speed limits.

CHAPTER 6. EVENT MODEL

The crash event analysis is an important part of the overall in-service safety evaluation of barriers. This intermediate phase of the crash occurrence process is where the barrier presence plays the important role of redirecting the sequence of events toward less severe ones. The crash event analysis serves as the important link between the onset of a crash occurrence process and its final outcome - the injury severity of individuals involved in the crash.

A multinomial logit model with variable outcomes was developed to analyze the effect of barriers as well as other influencing factors. Statistical modelling framework, variable processing, summary statistics of the data, and modelling results are discussed.

6.1 Introduction

For a given roadway segment, the purpose of eliminating crashes with roadside dangerous events using barriers is difficult to accomplish although the risk can be effectively reduced. In particular, when only one side of a directional segment has a barrier installed, roadway hazardous events can occur from the other side. Even for a directional segment with both its median and roadsides protected with barriers, hazardous events may still occur since barriers do not always work as expected.

For example, a median cable barrier is typically placed in Indiana near one of the median edges. A vehicle entering a wide median through the other edge is exposed to the potentially damaging impact of a ditch located in the median center. In another case, a tall vehicle hitting a guardrail at a high speed may roll over after the impact.

Using barriers may also increase some undesirable events. Our inspection based on the police narratives and collision diagrams in crash reports revealed that after running off the roadway and colliding with a barrier, some vehicles bounced off the barrier and were redirected back to the on-road traffic to collide with other vehicles.

Thus, most of the time, a barrier reduces the risk of hazardous events while increasing additional events, such as the mentioned redirecting of a vehicle that may lead to a multi-vehicle collision. The follow-up questions of this study are:

- By what percentage can cross-median crashes be reduced after a median barrier is installed?
- How less likely would a crash result in a hazardous event after a barrier is installed?
- How likely will a crash end up being a barrier collision given that the barrier is installed?
- How likely will an errant vehicle bounce off the barrier and be redirected to collide with other on-road vehicles?
- What factors influence these probabilities?

Therefore, how to quantify the change in the probabilities of those barrier-relevant hazardous events due to the installation of barriers was not only important in gaining insight into the safety impact, but also was critical in the evaluation of the overall in-service performance of the barriers. It is important to note that the aforementioned probabilities were conditioned on a barrier-relevant crash having occurred. Given the existence of the large variety of actual hazardous events, events in similar fashions were combined in this study to form a relatively smaller number of event categories.

To address the above questions, a multinomial logit model with variable outcomes was developed to predict the probability of a barrier-relevant crash resulting in each considered event category on a given segment with given roadway and roadside characteristics. The model also provided insight about how the variables affected the involved event probabilities.

6.2 Categories of Events

6.2.1 Universal Event Set

As mentioned in Section 4.4.2, the actual hazardous event for each barrier-relevant vehicle was identified by interpreting the crash narratives and diagrams documented in the police report. The originally-recorded barrier-relevant events, however, covered a large variety of collisions with roadside objects and non-collision events. To simplify the interpretation and modeling, those original events with their hazardousness in similar fashions were grouped into seven event categories. The seven event categories formed a universal event set, which includes all the possible events for a barrier-relevant vehicle to encounter on a barrier or non-barrier segment.

The universal event set includes:

- Event XH: cross-median head-on event
- Event XNH: cross-median non-head-on event
- Event RHV: redirected and hit another vehicle event
- Event MB: median barrier collision event
- Event SB: roadside barrier collision event
- Event HR: non-cross-median high-risk event
- Event MR: non-cross-median moderate-risk event

Below is the detailed description of each event:

- Event XH designates an event in which an errant vehicle crosses the median, enters the opposite roadway, and strikes at least one vehicle in the opposite direction. The occurrence of event XH is rare, but once it occurs the occupants involved are severely injured.
- Event XNH designates an event in which an errant vehicle crosses the median, enters the opposite roadway, and stops at the opposite roadway or the opposite roadside without striking opposite direction vehicles. Event XNH is similar to event XH, but the former is normally less dangerous. Median barriers are primarily used to prevent the occurrence of events XH and XNH
- Event RHV designates an event in which a vehicle departs from the roadway first, but then is redirected back to its roadway (due to driver's correction or rebound from a collided object), and eventually collides with at least one normal driving on-road vehicle.
- Event MB designates an event in which an errant vehicle collides with a median barrier. This event can be further divided based on the type and offset of the collided median barrier.
- Event SB designates an event in which an errant vehicle collides with a roadside barrier (i.e. guardrail).
- Event HR designates an event in which an errant vehicle rolls over or collides with a rigid fixed object, such as a tree, utility pole, bridge pier or abutment,

overhead sign post, light/luminaire support, other post/pole or support, wall/building/tunnel, embankment, culvert, etc. Barriers may be used to prevent a HR event.

- Event MR designates an event in which an errant vehicle collides with a non-rigid fixed object, such as a highway traffic sign post, ditch, crash cushion, fence, mailbox, etc. Barriers are not used to prevent an MR event. However, if a barrier happens to be there, those events are also prevented.

We can see that events XH and RHV involve multiple vehicles while other events normally just have a single vehicle involved.

6.2.2 Vehicle and Crash Event Category Assignment

A barrier-relevant vehicle might be involved in multiple events at the same time. This study used the most hazardous event category to represent its final assigned event category. The ranking for different event categories based on the relative hazardousness were (from the most hazardous to least hazardous): XH > XNH > HR > RHV > MB > SB > MR.

Other than vehicles, each barrier-relevant crash was also assigned to an event category. The assignment was based on the event category for its involved barrier-relevant vehicles. If a barrier-relevant crash involved multiple barrier-relevant vehicles, the most hazardous event category across vehicles was used to represent the crash event category based on the aforementioned event category ranking.

6.2.3 Conditional Event Set

It should be noted that not all of the event categories were eligible outcomes at the same time for a barrier-relevant crash. Which event category was eligible for a crash to result in depended on the median and roadside characteristics (or scenarios) of the corresponding roadway segment. For example, for a crash on a non-barrier segment, events MB and SB are not eligible. Likewise, events XH and XNH were not eligible to a crash on a segment with a median barrier installed. Note that this is based on what we found from our sample for this study, although there are some previous studies that found cross-median events were not eliminated with median barriers (see more discussions in Section 8.3).

Thus, it was important to define a conditional event set composed of only the eligible events for each crash. The conditional event set was conditioned on the median and roadside characteristics (i.e. whether a barrier was installed in the median or on the roadside). So for a crash on a given roadway segment, the conditional event set can be summarized as follows:

- Both median and roadside barriers installed: {RHV, MB, SB, HR, MR}
- Only median barriers installed: {RHV, MB, HR, MR}
- Only roadside barriers installed: {XH, XNH, RHV, SB, HR, MR}
- No barriers installed: {XH, XNH, RHV, HR, MR}

We can see that each conditional event set is a subset of the universal event set. Within a given conditional event set, the sum of the probabilities for all the individual event categories is equal to 1. Event MB is a mutually exclusive event of events XH and

XNH, reflecting that the presence of median barriers does not allow the occurrence of any cross-median event (at least for the data collected in this study). For now, the function of installing barriers can be summarized as adding or eliminating some event categories in the conditional event set, and re-distributing the share (i.e., the probability) of each event category.

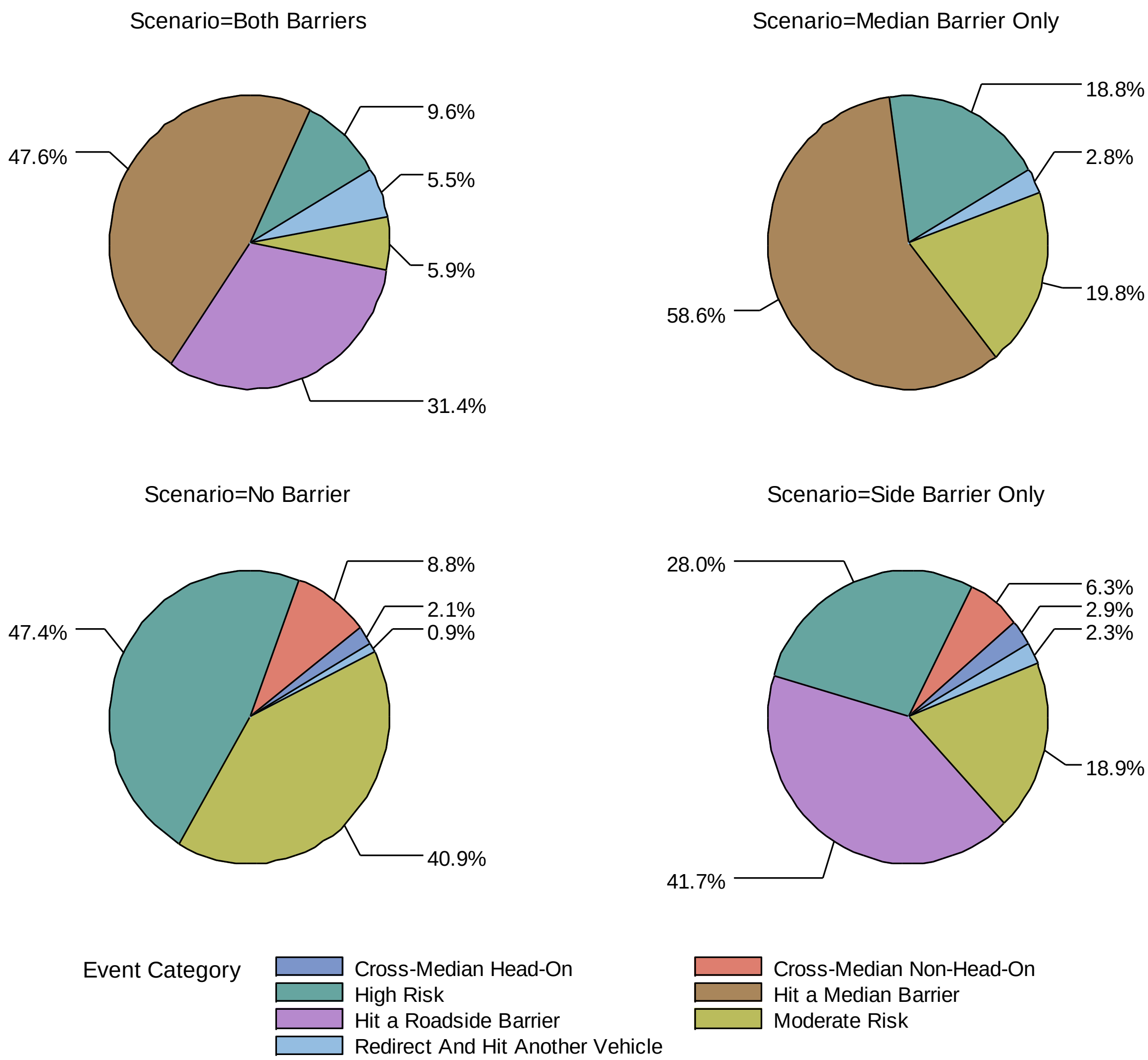


Figure 6.1 Distribution of Different Event Categories

6.2.4 Distribution of Different Event Categories

Figure 6.1 illustrates the share of different event categories under different median and roadside scenarios (combined scenarios) based on the data collected for this study. Cross-median events (events XH and XNH) comprised about 9% to 11% of all the barrier-relevant crashes on segments with no median barriers installed. Cross-median head-on events (event XH) separately comprised 2% to 3%.

Non-cross-median high-risk and non-cross-median moderate-risk events (events HR and MR) are the two most common event categories when a segment was not protected by barriers. Their dominance was overtaken by barrier collision event categories (events MB and SB) once a barrier was installed on a segment. However, non-cross-median high-risk and non-cross-median moderate-risk events were not eliminated even when both sides of a segment were protected with barriers. Particularly, non-cross-median high-risk events comprised 5.5% of the crashes. This result reflects the fact that vehicles still face the risk of rolling over if a barrier is placed far away or a rollover can occur after a collision with a barrier.

For redirected vehicle events (event RHV), it is interesting to see how their share of crashes changed with the installation of barriers. Redirected vehicle events comprised only about 1% of the crashes when there was no barrier installed on a segment, but that share increased to about 2% to 3% when only one side of roadway was shielded with a barrier and increased to 5.5% when both sides of the roadway were protected by barriers. This result reflects the observed tendency for barriers to increase the probability of vehicle redirected events.

Although Figure 6.1 demonstrates the general trend of how crash event categories were distributed on segments by different median and roadside conditions, the actual event category probability for a barrier relevant crash under a given roadway may also depend on other variables, such as the median width, the barrier type and offset, the roadside hazard rating, etc. The following event model was used to estimate the event category probability with taking care of all the significant influencing variables.

6.3 Modelling Framework and Variables

A multinomial logit model with variable outcomes was developed based on a number of 2,049 barrier relevant-crashes that occurred from 2003 to 2012 on the selected homogenous segments. The model used roadway and roadside related variables to estimate the probability of a barrier-relevant crash to be involved in different event categories. Each observation is a barrier-relevant crash with its event category assigned, its conditional event set specified, and its roadway and roadside information linked.

Multinomial logit models have been applied by many researchers to model crash-injury severity (Lee and Mannering, 2002; Ulfarsson and Mannering, 2004). Different with the standard multinomial logit models, the developed multinomial logit model with variable outcomes allowed that the number of eligible events varied from one observation to another, which depended on the median and roadside characteristics as discussed in Section 6.2.3. The econometric software, NLOGIT, was used to estimate the developed multinomial logit model with variable outcomes (Greene, 2007).

Some of the advanced unordered discrete outcome models reviewed in Section 2.3.2 possibly could be used to model the event outcomes. This study attempted the use of the nested logit models and mixed logit models on the basis of the developed simple multinomial logit model. Several nesting structures were specified under the nested logit model framework but the corresponding coefficients for the logsum parameters did not show to be greater than 0 and less than 1, which indicated that the IIA assumptions were not violated by the simple multinomial logit model. Then the mixed logit models were attempted with a normal distribution assumed for each random parameter variable. It was found that no variable had an observation-specific effect. Thus, the simple multinomial logit model ultimately was selected to model the proportions of crashes resulting in different event outcomes.

In the modelling framework of a multinomial logit model, the propensity function of i th barrier-relevant crash resulting in j th event category is in a linear form:

$$U_{ij} = \boldsymbol{\beta}_{\mathbf{j}} * \mathbf{X}_{\mathbf{ij}} + \varepsilon_{ij} \tag{6.1}$$

Where $\mathbf{X}_{\mathbf{ij}}$ is a vector of measurable roadway and roadside characteristics of the directional segment on which i th barrier-relevant crash occurred. $\boldsymbol{\beta}_{\mathbf{j}}$ is a vector of estimated coefficients for j th event category and ε_{ij} is the error term and assumed to be generalized extreme value distributed (McFadden, 1981). Then the expected value of the propensity is as follows:

$$\overline{U}_{ij} = \boldsymbol{\beta}_{\mathbf{j}} * \mathbf{X}_{\mathbf{ij}} \tag{6.2}$$

The probability of i th barrier-relevant crash resulting in j th event category out of a number of J_i eligible event categories is calculated as:

$$P(E_{ij}) = \frac{\exp(\boldsymbol{\beta}_{\mathbf{j}} * \mathbf{X}_{\mathbf{ij}})}{\sum_{\forall j \in J_i} \exp(\boldsymbol{\beta}_{\mathbf{j}} * \mathbf{X}_{\mathbf{ij}})} = \frac{\exp(\overline{U}_{ij})}{\sum_{\forall j \in J_i} \exp(\overline{U}_{ij})} \tag{6.3}$$

It should be noted that the denominator term in Equation 6.3 is the summation of the exponentiations of all the event categories in the conditional event set, rather than the summation based on the universal event set. For example, the probability of event RHV for a barrier-relevant crash on a segment with only median barrier installed is

$$P(E_{RHV}) = \exp(\overline{U}_{RHV}) / [\exp(\overline{U}_{RHV}) + \exp(\overline{U}_{MB}) + \exp(\overline{U}_{HR}) + \exp(\overline{U}_{MR})],$$

whereas the same event probability for a crash on a segment with no barrier installed is

$$P(E_{RHV}) = \exp(\overline{U}_{RHV}) / [\exp(\overline{U}_{XH}) + \exp(\overline{U}_{XNH}) + \exp(\overline{U}_{RHV}) + \exp(\overline{U}_{HR}) + \exp(\overline{U}_{MR})].$$

The coefficient for each propensity function was estimated using maximum likelihood estimation. It should be noted that all the propensities estimated were relative propensities. That is, what determined an individual event category’s probability was not how large its propensity was but rather how different it was compared to the propensities of other event categories.

The most important explanatory variables were median and roadside characteristics, which were represented by different median and roadside scenarios (including barriers and non-barriers) respectively. See Section 3.2 for more details. Six categories were included in the median scenarios divided based on the median width, barrier type and offset. Three categories were included in the roadside scenarios divided based on the presence of a roadside guardrail and roadside hazard rating.

In the modelling, all median scenarios as a whole were taken as a categorical variable, with each individual scenario coded as a binary indicator variable (i.e., dummy variable). One binary variable was removed before modelling and the scenario this variable represented was the reference condition to which the other scenarios (represented by other binary variables) were compared. The roadside scenarios were processed in the same way.

Table 6.1 Summary of Statistics of Considered Variables in the Event Model (Crash Level)

Variables	Categories	Count	Percentage (%)
Event category	Non-cross-median high-risk event	627	30.6
	Median barrier wall collision	382	18.64
	Nearside median cable barrier collision	62	3.03
	Far-side median cable barrier collision	42	2.05
	Median guardrail (face) collision	69	3.37
	Non-cross-median moderate-risk event	551	26.89
	Vehicle redirected and hit another vehicle	47	2.29
	Roadside guardrail collision	158	7.71
	Cross-median head-on	23	1.12
	Cross-median non-head-on	88	4.29
Functional class and speed limit	Freeway with a speed limit 65mph or higher	1,720	83.94
	Freeway with a speed limit 60mph or lower	249	12.15
	Non-freeway	80	3.91
Horizontal curve	Left curve	77	3.76
	Right curve	93	4.54
	Tangent	1,879	91.7
Urban area Indicator	Urban	686	33.48
	Rural	1,386	66.52
Median scenario	Nearside Cable Barrier (offset <=30 feet)	111	5.42
	Far-side Cable Barrier (offset>30ft)	95	4.64
	Concrete Barrier	624	30.45
	Guardrail	168	8.2
	Narrow Median (width<=50ft)	61	2.98
	Wide Median (width>50ft)	990	48.32
Roadside scenario	High-hazard roadside (hazard rating 3 to 7)	914	44.61
	Low-hazard roadside (hazard rating 1 or 2)	689	33.63
	Guardrail	446	21.77
Number of lanes	Two lanes	1,457	71.11
	Three lanes	512	24.99
	Four lanes	34	1.66
	Five lanes	46	2.24

Other roadway and roadside related-variables attempted in the modelling included traffic volume, presence of a horizontal curve, roadway functional class, and speed limit. Table 6.1 shows the summary statistics of variables considered in the development of the event model.

6.4 Modelling Results

The modelling results are shown in Table 6.2. The non-cross-median high-risk event (event HR) was used as the reference response category (or baseline category) to which all other event categories to compare with, and therefore its propensity is set as 0 and no estimated coefficients were available for this category. In Table 6.2, the coefficient value of a given variable under a given event category reflects how much the propensity for that event category (relative to the reference response category, which is event HR) is changed due to this variable (compared to the variable's corresponding reference condition), assuming other variables were held constant.

For example, the urban/rural binary variable used the rural condition as the reference condition. The coefficient of the urban indicator was 0.563 in the event RHV, which indicated that compared to rural roads, a barrier-relevant crash that occurred on urban roads resulted in a 0.563 increase in the propensity of event RHV relative to the reference event HR. In other words, the odds of event RHV vs. event HR were increased by exp(0.563) if a barrier-relevant crash occurred on a urban road relative to a rural road.

Table 6.2 Parameter Estimates (t value) of the Event Model (Multinomial Logit Model)

Variable	XH	XNH	RHV	MR	MB	SB
Constant	-1.636 (-2.96)	-0.621 (-1.68)	-4.066 (-12.64)		1.325 (15.03)	1.122 (5.54)
M_NB_Nar (Reference)					-	
M_NB_Wide	-1.618 (-2.8)	-1.099 (-2.83)		-0.347 (-3.72)	-	-1.035 (-3.73)
M_BW	-	-	1.893 (4.47)			
M_CB_Near	-	-	2.288 (3.86)			
M_CB_Far	-	-			-0.727 (-3.25)	
M_GR	-	-	1.890 (3.81)		-0.649 (-3.52)	
S_NB_High (Reference)						-
S_NB_Low				0.324 (3.01)		-
S_GR	0.776 (1.48)		1.452 (4.48)		0.613 (3.31)	
Rural area (Reference)						
Urban area			0.563 (1.6)			
FrLE60 (Reference)						
FrGE65						0.337 (1.30)
No. of Obs	2049					
LogL	-2252.9					
AIC	4545.8					

The non-cross-median high-risk event (i.e., event HR) is set as the reference category for all the event categories.

A blank cell indicates the coefficient for this variable is not significantly different from the coefficient for its reference condition.

"-" indicates the response event is not an eligible event (i.e., the probability is always equal to 0) when the corresponding explanatory variable is equal to 1.

XH: cross-median head-on event.
XNH: cross-median non-head-on event.
RHV: redirected and hit another vehicle event.
MB: median barrier collision event.
SB: roadside barrier collision event.
HR: non-cross-median high-risk event.
MR: non-cross-median moderate-risk event.
M_NB_Nar: median 50 feet or narrower and no median barrier.
M_NB_Wide: median wider than 50 feet and no median barrier.
M_BW: median concrete barrier wall placed in the center of a narrow median.
M_GR: median guardrail placed in the center of a median or at the nearside edge.
M_CB_Near: median cable barrier with a lateral clearance 30 feet or less to the travelled way.
M_CB_Far: median cable barrier with a lateral clearance more than 30 feet to the travelled way.
S_GR: roadside guardrail.
S_NB_Low: no guardrail, roadside hazard rating: 1 or 2.
S_NB_High: no guardrail, roadside hazard rating from 3 to 7.
FrLE60: non-freeway or freeway with speed limit lower than or equal to 60mph.
FrGE65: freeway with speed limit greater than or equal to 65mph.

It is important to note that a variable's coefficient under an event category reflects how it compares to the reference event category and does not directly reflect the effect of the variable on the eventual probability of this event, since the change of this variable on the probability of the event also depends on how this variable performs in categories other than this category. For the above example with the effect of urban/rural, for example, if its coefficients for categories such as events XH, XNH, and MR were also positive and were even larger than the coefficient for category RHV (which is not the case with the actual coefficient as shown in the table), it would have been very likely that the actual probability of event RHV would have decreased with urban area even though urban driving increases the odds of event RHV vs. event HR locally.

6.4.1 Pair Comparison between an Event of Interest and Event HR

For now, let us first focus on the pair comparison between an event category of interest and the reference event category (i.e., event HR) without considering how other event categories come into play. The coefficient of each variable under the interested event category reflects how this variable relative to its reference condition changes the odds of this event vs. the event HR. It should be noted that an increase/decrease in the odds might be attributed to either an increase/decrease in the probability of the event category of interest (the numerator in calculating the odds), or decrease/increase in the reference event HR (the denominator in calculating the odds), or a combination of both. Engineering judgment was used to decide whether the numerator, the denominator, or both of them caused the odds change.

Pair comparison between events XH and HR

The coefficients in the column for event XH (cross-median head-on event) were relevant to this comparison. The coefficients for median scenario M_NB_Wide (median wider than 50 feet and no median barrier) under event XH was significantly less than 0, indicating that the median scenario M_NB_Wide decreased the odds of event XH vs. event HR, compared to the reference median scenario M_NB_Nar (median 50 feet or narrower and no median barrier). This result was expected since a wide median not only provides a larger recovery zone for an errant vehicle to take action to prevent crossing the median, but also gives the opposite-direction traffic more time to predict and react to the median-crossing behavior of vehicles.

Note that the coefficients of the median barrier relevant scenarios (M_BW, M_GR, M_CB_Near, and M_CB_Far) for event XH were not provided by the model. This situation does not mean that those scenarios did not influence the probability of event XH. On the contrary, our data showed that those median barrier scenarios totally eliminated the possibility of event XH, which also could be perceived as their coefficients being indefinitely negative, such that once the median barrier was present, the propensity of event XH was indefinitely negative and thus the probability of event XH was equal to 0 (see Equation 6.3).

Roadside scenarios also were shown to have a significant effect. Roadside scenario S_GR (roadside guardrail) was shown to increase the odds of event XH happening vs. event HR. Given that the roadside environment should not affect what happens in the median most of time, we attributed the odds increase to the reduction in non-cross-median high-risk events due to the use of roadside guardrails.

Pair Comparison between events XNH and HR

The coefficients in the column for event XNH (cross-median non-head-on event) were relevant to this comparison. For the median scenarios, the pair comparison between events XNH and HR showed results similar to the aforementioned event XH vs. event HR comparison. Likewise, the median scenarios with median barriers installed eliminated the occurrence of event XNH and thus their coefficients were not available in the model result output.

The median scenario M_NB_Wide (wide median without barrier) was the only variable shown to significantly reduce the odds of event XNH vs. event HR.

Pair comparison between events RHV and HR

Coefficients in the column for the event RHV (redirected and hit another vehicle event) are relevant to this comparison. The results revealed that the odds of event RHV vs. event HR are increased by median barrier scenarios (M_BW, M_GR and M_CB_Near), except the far-side median cable barrier scenario (M_CB_Far). The odds increase from the median barrier walls, median guardrails, and near-side median cable barriers could be explained by a combination of barriers' two effects: 1) those median barriers are either rigid or relatively placed closer to the travelled way, which makes ROR drivers more likely to overcorrect their vehicles back to roadway and get collided with normally driving vehicles; 2) those median barriers are effective in reducing the occurrence of high hazard events in medians such as rollover events.

For the roadside scenarios, roadside guardrails were also shown to increase the odds of event RHV vs. event HR in a fashion similar to rigid or close-placed median barriers. Moreover, crashes that occurred on urban areas were found more likely to increase the odds of event RHV vs. event HR relative to rural areas. This result could be related to the difficulty of drivers to maneuver their vehicles to avoid a collision with a redirected vehicle in the high traffic volumes common on urban roads.

Pairwise comparison between event MR and HR

The coefficients in the column for event MR (non-cross-median moderate-risk event) were relevant to this comparison. The modeling results suggest that the odds of event MR vs. event HR decreased by the median scenario M_NB_Wide (median wider than 50 feet and no median barrier) but increased by the roadside scenario S_NB_Low (no guardrail, roadside hazard rating: 1 or 2). The odds increase from scenario M_NB_Wide might be related to the fact that compared to the reference condition M_NB_Nar (median 50 feet or narrower and no median barrier), M_NB_Wide had a wider median, thus, vehicles might be more likely to roll over in the median instead of crossing the median. In other words, widening the median might bring more non-cross-median high-risk events, such as rollovers, although they are effective in reducing cross-median events as we discussed earlier.

For the odds decrease from the roadside scenario S_NB_Low, this was expected since it reflected that the more forgiving roadside reduced the occurrence of high hazard events more than that of the moderate hazard events.

Pairwise comparison between events MB and HR

The coefficients in the column for event MB (median barrier collision event) were relevant to this comparison. For the median scenarios, it should be noted that the reference condition was set as M_BW. The scenarios M_NB_Nar (the reference condition for other event categories) and M_NB_Wide eliminated event MB so neither of them could be selected as an eligible reference condition for median scenario comparisons under event MB. So the negative coefficients for median scenario M_CB_Far and M_GR indicated that barrier collision events were less likely to occur on segments with far-side median cable barriers or median guardrails, compared to segments with median concrete barrier walls. This reflects a trend that the more rigid and closely placed the median barrier is, the more likely the median barrier collision event will occur.

The positive coefficient of the roadside scenario S_GR suggests that, compared to a non-barrier roadside (S_NB_High and S_NB_Low), a barrier-relevant vehicle was more likely to result in hitting a median barrier if its roadside was protected with a guardrail. We attribute this odds increase to the effectiveness of roadside guardrails in reducing the occurrence of high hazard events rather than believing that median barrier collision events increased with the installation of roadside guardrails.

Pairwise comparison between events SB and HR

The coefficients in the column for event SB (roadside barrier collision event) were relevant to this comparison. For the median scenarios, the scenario M_NB_Wide was shown to decrease the odds of event SB vs. event HR relative to the reference scenario M_NB_Nar. We do not attribute the odds decrease to any change in roadside barrier collisions but to the relatively more non-cross-median high-risk events, such as rollovers, which are expected on wide medians compared to narrow medians as previously mentioned. For the roadside scenarios, the coefficients for those non-roadside barrier scenarios ((S_NB_High and S_NB_Low) were not provided by the model since they eliminated event SB.

In addition, the odds for freeways with higher speed limits were found to be higher, which was expected since vehicles are more likely to lose control and collide with roadside barriers under higher travelling speeds.

6.4.2 Overall Comparison among All Involved Event Categories

The previous pair comparison provides details of how a variable influences the relative probability of an event category of interest vs. the reference event category (event HR). However, the final probability of an event category of interest depended on how the variable changed the probability of other event categories. To better assess the overall influence of a variable on all those involved event categories in the big picture, it is important to know how a variable of interest performed in all of the involved events together. This process is more complicated than simple pair compassion, and we focused only on the general trend.

Median scenarios

As reflected from the coefficients of the median scenario M_NB_Wide (wide median with no barrier) across different event categories, the scenario substantially reduced the three odds values (i.e., XH vs. HR, XNH vs. HR, and SB vs. HR), which suggests a tendency that a barrier-relevant crash that occurred on a segment with a wide median and no barrier was less likely result in cross-median events (head-on or non-head-on) relative to a segment with a narrow median with no barrier. The tendency was expected since the use of a wide median with no barriers not only provides a larger recovery zone for ROR vehicles to take action to prevent crossing the median but also allows vehicles in the opposite direction to evade median-crossing vehicles.

All of the median barrier scenarios, except the far-side median cable barrier, were found to be more likely associated with vehicle redirected events compared to the non-barrier median scenarios. The scenarios for median barrier wall and near-side median cable barrier were found to be more likely associated with barrier collision events relative to median guardrails and far-side median cable barriers. Overall, this reflects a trend that the more rigid and closely placed a median barrier is, the more likely that vehicle redirected events and median barrier collisions will occur.

Roadside scenarios

From the coefficients for S_NB_Low across different categories, we can see that all of them were not significant except the coefficient under event MR, which suggests that two non-barrier roadside scenarios were similar in terms of their distribution of different event categories. The only difference was that the scenario with the lower hazard rating tended to be more associated with non-cross-median moderate-risk events.

All of the significant coefficients for the roadside guardrail scenario were positive, indicating that the installation of roadside guardrails might increase the relative propensity of those event categories (events XH, RHV, and MB). Actually, we believe the propensity increase in cross-median head-on events and median barrier collision events due to roadside guardrail use was more of a reflection of the barriers' effectiveness in the reduction of other events such as high and non-cross-median moderate-risk events. However, the absolute probability of the vehicle redirection events is believed to increase with the use of roadside guardrails since the coefficient under this event category was much larger than those under the other two categories.

Other variables

A barrier-relevant crash that occurred in urban areas was more likely to result in vehicle redirection events as indicated by the significant coefficient under the event RHV. This was expected because the on-road traffic volumes in urban areas gives redirected vehicles fewer chances to avoid vehicle-vehicle collisions. In addition, crashes that occurred on a freeway with a higher speed limit were more likely to be associated with roadside barrier collision events since drivers are more likely to lose control and collide with roadside barriers due to higher travelling speeds.

6.5 Chapter Summary

A barrier reduces the risk of hazardous events and may increase additional events such as redirecting of a vehicle that may lead to a multiple-vehicle collision. It is important to quantify the change in the probabilities of those barrier-relevant hazardous events with the installation of barriers. The barrier-relevant events are grouped into seven event categories:

- Event XH: cross-median head-on event
- Event XNH: cross-median non-head-on event
- Event RHV: redirected and hit another vehicle event
- Event MB: median barrier collision event
- Event SB: roadside barrier collision event
- Event HR: non-cross-median high-risk event
- Event MR: non-cross-median moderate-risk event

This study developed a statistical model to identify the influencing roadway and roadside characteristics for the barrier-relevant crashes that resulted in each considered event category. The developed model can be used to predict the probability of a barrier-relevant crash to fall into each considered hazardous event category on a given segment with given roadway and roadside characteristics.

A multinomial logit model with variable outcomes was developed based on a total of 2,049 barrier relevant crashes that occurred on a number of 1,258 directional segments from 2003 to 2012. Based on the modelling results, when a directional segment had no median barrier installed, a barrier-relevant crash was less likely to result in cross-median events if the median width was wider than 50 feet, which indicates that widening a median can substantially reduce the cross-median events, particularly for multiple-vehicle head-on collisions. Caution should be given to the potential increase in non-cross-median high-risk events, such as median rollover events due to the use of a wide median.

When a median barrier was present, the collected data did not show any cross-median events. This suggests that the use of median barriers is very effective in reducing or even eliminating cross-median events. The total elimination would have been hard to achieve if we had had a larger sample size, as found in some studies. The caution of using median barriers is that errant vehicles are more likely to be redirected back to roadway and collide with other on-road vehicles. In addition, there are still a small number of vehicles rolling over after they make contact with barriers, although generally median barrier are effective in reducing median rollover events.

The barrier type and offset of median barriers were also found to affect the event probability distribution. The modelling results indicated that the more rigid and more closely placed the median barrier was, the more likely a barrier-relevant crash would result in the redirected vehicle events and the median barrier collisions.

When a roadside had no barrier installed, it was found that a roadside with a lower roadside hazard rating (more forgiving) tended to be more likely associated with non-cross-median moderate-risk event. Thus, other events which are more hazardous than non-cross-median moderate-risk events would become less likely. The use of roadside guardrails was shown to effectively reduce the probability of non-cross-median high-risk events such as fixed object collisions and rollover events. Like median barriers, the caution on roadside guardrail use should be the potential increase in the redirected vehicle events.

The study also found that the probability of redirected vehicle events increased if a barrier-relevant crash occurred in urban areas and that the probability of roadside barrier collisions was higher on freeways with a speed limit of 65 mph or higher.

Overall, the developed model provides insights on evaluating different median and roadside scenarios in terms of their effects on the probability of different hazardous events. The most important part of the use of the model, however, is probably that it provides the estimated parameters to be used to describe the propensity of each hazardous event category. Those propensity functions will be later used in Chapter 8 to predict the events' probabilities for different median and roadside scenarios, which will be an important part of the overall in-service safety performance evaluation of barriers.

CHAPTER 7. INJURY MODEL

This chapter presents the injury analysis, which addresses how hazardous events relevant to barriers affect the probability of a vehicle occupant's injury (fatal, incapacitating, or non-incapacitating). This injury analysis was an important part of the overall in-service safety evaluation of barriers. The study developed a binary logit model with mixed effects to analyze the effect of hazardous events as well as other influencing factors. The statistical modelling framework, variable processing, summary statistics of the data, and modelling results are discussed.

7.1 Introduction

Collisions with barriers are supposed to be less risky than the events they prevent. Given the fact that the barrier itself is also a hazard that can cause injury to vehicle occupants, there would be no need to consider installing a barrier as a viable alternative if barrier collisions tend to be more severe. Therefore, an important question addressed in this study relates to how much more forgiving those barrier collisions are compared to the hazardous events.

Even for barriers collisions, their associated injury risk can vary a lot since the rigidity of different types of barriers differs. They can be as flexible as cable barriers, as rigid as concrete barrier walls, or somewhere in between as are median guardrails. Even for barrier collisions within the same type, different placements of the barriers may lead to different injury outcomes.

For example, cable barriers in Indiana are used in medians around 60 feet wide and are placed closer to one side of the median edge with an offset around 16 feet. Therefore, for vehicles colliding with cable barriers after entering the median from the other side, their injury risks are very likely to be different compared to cable barrier collisions from the near side as a result of different lateral clearances and impact angles. Guardrail collisions are another example. Since guardrails can be used either in medians or on roadsides, the injury outcomes also may differ between median guardrail collisions and roadside guardrail collisions.

Thus, the objective of this study was to evaluate the difference in the injury outcomes associated with different hazardous events, including hitting a barrier under different type-location scenarios as well as those events that barriers are supposed to prevent. An event's hazardousness is measured as the probability of a vehicle occupant sustaining a certain injury level from being involved in the event. The intended outcome of this study was the development of a model to predict this probability. As with the frequency analysis and event analysis in Chapters 5 and 6, the injury analysis presented here is also an important part of the overall safety in-service performance evaluation of road barriers.

7.2 Data and Variable Description

7.2.1 Injury Outcome Levels

The injury outcome levels were based on the police-reported KABCO scale (K: fatality, A: incapacitating injury, B: non-incapacitating injury, C: possible injury, and O: property-damage-only). Vehicle occupant-specific information, such as age, gender, and injury level, were recorded only for the driver and the injured passengers. Property-damage-only was assumed for vehicle occupants whose injury level information was not reported by the police. An observation for this study was a barrier-relevant vehicle occupant with available and relevant information about the injury level, vehicle type, driver age, event category, etc.

7.2.2 Event Categories

The actual hazardous events were combined into event categories and ten event categories considered in this chapter are as follows:

- Event XH: cross-median head-on event
- Event XNH: cross-median non-head-on event
- Event RHV: vehicle redirected and hit another vehicle event
- Event MB/BW: median concrete barrier wall collision
- Event MB/GR: median guardrail (face) collision
- Event MB/CB1: nearside median cable barrier collision (offset 30 ft or less)
- Event MB/CB2: far-side median cable barrier collision (offset more than 30 ft)
- Event SB: roadside guardrail collision
- Event HR: non-cross-median high-risk event (e.g. rollover or hitting a sturdy fixed object)
- Event MR: non-cross-median moderate-risk event (e.g. hitting a weak object, running over a ditch, etc).

These considered events are consistent with those in Chapter 6 (see Section 6.2.1) except that the median barrier collision event category is now further classified by the median barrier type and location (event MB in Chapter 6 was extended to event MB/BW, event MB/GR, event MB/CB1 and event MB/CB2 in this chapter). See Section 6.2.1 for a detailed description of each event category.

Recall that in the event analysis presented in Chapter 6, the information for barrier types and offsets was contained in the median and roadside scenarios, which were used as explanatory variables to predict the probability of barrier collision events as well as the probability for other hazardous event categories. In this chapter, the explanatory variables are not median and roadside scenarios but rather the event categories.

7.2.3 Data Summary

The data sample for the injury analysis was composed of a total of 3,299 individual vehicle occupants in 2,049 barrier-relevant crashes between 2003 and 2012, which occurred on a number of 732 segments out of 1,258 total collected homogeneous segments. Note that for those segments with cable barriers installed after 2008, only crashes from the year after the installation through 2012 were assigned.

The important information included the following: injury level, event category, vehicle type, speed limit, presence of aggressive driving, driver's gender and age, light condition, weather condition, road surface condition, AADT, etc. Table 7.1 shows the selected statistics of variables considered in the injury model. Table 7.2 shows the frequency of occupants with different injury outcomes classified by event category.

Table 7.1 Selected Statistics of Variables Considered in the Injury Model (Occupant Level)

Variables	Categories	Count	Variables	Categories	Count
Crash severity level	Fatality (K)	20	Driver indicator	Yes	2124
	Incapacitating (A)	63		No	1175
	Non-incapacitating (B)	545	Driver age	55 and older	452
	Possible injury (C)	40		younger than 55	2847
	Property damage only (O)	2631	Driver gender	Male	2112
Event category	Non-cross-median high-risk event	1022		Female	1187
	Median barrier wall collision	561	Vehicle type	Motorcycle	14
	Nearside median cable barrier collision	96		SUV	439
	Far-side median cable barrier collision	55		Truck	273
	Median guardrail (face) collision	117		Car and other	2573
	Non-cross-median moderate-risk event	854	Aggressive driving	Yes	100
	Vehicle redirected and hit another vehicle	150		No	3199
	Roadside guardrail collision	241	Rural indicator	Rural	2196
	Cross-median head-on	67		Urban	1103
	Cross-median non-head-on	136	Horizontal curve	Left curve	133
Functional class and speed limit	Freeway with a speed limit 65mph or higher	2813		Right curve	126
	Freeway with a speed limit 60mph or lower	376		Tangent	3040
	Non-freeway	110	Road surface condition	Good (dry and clean)	1452
Weather condition	Clear	1222		Poor (ice, snow, etc.)	1326
	Cloudy	439		Wet	521
	Rain	432	Light condition	Daylight	1800
	Snow	710		Dawn or dusk	158
	Sleet or hail or freezing rain	240		Dark (lighted)	181
	Fog or smoke or smog	23		Dark (not lighted)	1158
	Severe cross wind	27		Unknown	2
	Blowing soil or snow	206			

7.3 Modelling Framework

As can be seen from the Tables 7.1 and 7.2, the number of fatal and incapacitating occupants was rather low. The infrequency of those more severe injury levels did not allow us to model them separately. Thus, we combined all three levels of police-reported injuries as one category - injury - for statistical analysis.

Table 7.2 Frequency of Occupants with Different Injury Levels (KABCO) by Event Category

Event Categories	Injury Levels					
	K	A	B	C	O	Total
Non-cross-median high-risk event	9	38	279	18	678	1022
Median barrier wall collision	0	6	78	7	470	561
Nearside median cable barrier collision	0	0	2	1	93	96
Far-side median cable barrier collision	0	0	5	0	50	55
Median guardrail (face) collision	0	2	19	0	96	117
Non-cross-median moderate-risk event	0	6	69	9	770	854
Vehicle redirected and hit another vehicle	1	1	18	0	130	150
Roadside guardrail collision	0	1	19	1	220	241
Cross-median head-on	9	4	15	0	39	67
Cross-median non-head-on	1	5	41	4	85	136
Total	20	63	545	40	2631	3299

A binary logistic regression model was used to estimate the vehicle occupant-based probability of injury. The observations of the original five severity levels were combined into two severity levels: 1) injury level (coded as “1”) representing the fatality, incapacitating and non-incapacitating and 2) non-injury level (coded as “0”) representing the possible injury and property-damage-only.

The unobserved heterogeneity of the crash counts and severity levels across roadway segments has been handled by various modeling approaches in the past (Ma et al., 2008; Milton et al., 2008; Anastasopoulos et al, 2012) while little has been done to take care of the heterogeneity across vehicles. The past literature (Yamamoto and Shankar, 2004; Eluru et al., 2010; Zhu and Srinivasan, 2011; Zou et al., 2014) indicates that shared unobserved heterogeneities for different vehicle occupants were also expected within the vehicle. Moreover, this study also considered the potential help from the pairing process of homogeneous segments by utilizing the commonality of the conditions within the segment pairs. Thus, a logistic model with several mixed effects was deemed suitable to account for possible correlation between the error terms of observations within the vehicles, segments, and segment pairs.

It is important to note that the unobserved heterogeneity across observations also might occur for the included explanatory variables, which would justify the use of a random parameters model. However, this study also focused on the implementation of the developed model to predict the injury likelihood of new observations, and using the random parameters models would increase the complexity of this prediction. A recent study by Chen and Tarko (2014) revealed that random effects models are a practical alternative to random parameters models. So a binary logit model with random effects was finally selected to model the injury outcomes.

We first attempted the model with three random effects (vehicle, segment, and segment pair) but this model failed to converge, possibly due to the modeling complexity or high correlation between segments and segment pairs. Then, two-level random effects models under two scenarios (vehicle and segment as the random effects and vehicle and segment pair as the random effects) were attempted. Finally, the model with the vehicle and segment pair as random effects was selected due to its smaller value of standard error over mean. Both distributions of the two random effects in this study were assumed to be normal. The binary logistic regression model with fixed and random effects is as follows:

$$\log\left(\frac{\pi_i}{1-\pi_i}\right) = \boldsymbol{\beta}\mathbf{X_i} + \nu_p + \omega_q \tag{7.1}$$

where:

π_i = probability of injury (fatality, incapacitating, or non-incapacitating) for vehicle occupant *i*,

$\boldsymbol{\beta}$ = vector of estimated coefficients for fixed effects,

$\mathbf{X_i}$ = vector of explanatory variable values for vehicle occupant *i*,

ν_p = random intercept for a segment pair *p*, $\nu_p \sim N(0, \sigma_\nu^2)$,

ω_q = random intercept for a vehicle *q*, $\omega_q \sim N(0, \sigma_\omega^2)$.

Table 7.3 Modelling Results of the Injury Model (Binary Logistic Regression)

Variable	Parameter Estimate	Standard Error	t-value	Odds Ratio
Constant	-0.531	0.135	-3.94	-
Occupant				
Driver	0.260	0.118	2.21	1.30
Non-driver	Reference			
Driver age				
Mature driver (age > 55)	0.276	0.162	1.70	1.32
Younger driver	Reference			
Vehicle type				
Truck	-0.437	0.217	-2.02	0.65
Motorcycle	3.338	0.928	3.60	28.15
Car, SUV and other	Reference			
Event category				
Cross-median head-on	0.608	0.347	1.75	1.84
Vehicle redirected and hit another vehicle	-1.079	0.311	-3.47	0.34
Median barrier wall collision	-0.858	0.172	-4.99	0.42
Median guardrail (face) collision	-0.883	0.329	-2.69	0.41
Nearside median cable barrier collision	-3.012	0.757	-2.10	0.05
Far-side median cable barrier collision	-1.596	0.536	-2.98	0.20
Roadside guardrail collision	-1.547	0.282	-5.49	0.21
Non-cross-median moderate-risk event	-1.671	0.168	-9.92	0.19
Non-cross-median high-risk and cross-median non-head-on*	Reference			
Road surface conditions				
Poor (ice, snow, loose material, etc.)	-1.224	0.137	-8.92	0.29
Wet surface	-0.538	0.172	-3.13	0.58
Good (dry and clean)	Reference			
Random effects				
Segment pair	0.070	0.079	-	-
Vehicle	1.374	0.177	-	-
Number of observations	3,299			
-2 Restricted log pseudo-likelihood	16,062.55			
Generalized chi-square	1,797.93			
Generalized chi-square / degree of freedom	0.55			

*The cross-median non-head-on event was not significantly different from the non-cross-median high-risk event. So it was also included in the reference category.

7.4 Discussion

Table 7.3 shows the modeling results of the develop injury model. Except for the segment pair, the variables included in this model were statistically significant at the 10% level. The random effects of segment pair were considerable but did not reach the 10% significance level. It was included due to its importance for this study.

The outcomes of non-cross-median high-risk event were used in the model as reference events to which the outcomes of other events were compared. It was found that a cross-median non-head-on event involved a risk of injury that was not statistically different from the risk imposed by a non-cross-median high-risk event. Thus it also was included in the reference category. The coefficients provided in Table 7.3 for different events, and particularly the odds ratios in the last column, reflect the difference in the risk of injury in a certain event and in the non-cross-median high-risk event.

7.4.1 Pair Comparisons across Events

Non-cross-median high-risk events vs. barrier collision events

Let us first discuss the forgiveness of barrier collision events relative to a non-cross-median high-risk event. The odds of injury associated with hitting a median concrete barrier wall were lower by 58% (odds ratio 0.42). It was 59% and 79% less risky to hitting a median guardrail face and to hitting a roadside guardrail face respectively (odds ratio 0.41 and 0.21). The comparative performance of a median cable barrier was even better, with a 95% and 80% reduction in the odds ratio for near-side and far-side installations, respectively.

Barrier collisions comparison

The direct comparison results across different types of barriers and their offsets could be obtained using their respective odds ratios as presented in Table 7.3. For instance, the odds of being injured by hitting a median guardrail face were 2% (0.41/0.42=0.98) lower than the odds for hitting a median concrete barrier. The odds of injury from hitting a near-side median cable barrier were 88% lower than hitting a median guardrail. This odds reduction for a far-side median cable barrier was lower and was equal to 49%. A cable barrier installed near the other side of the median is reached by a vehicle after driving across an uneven median surface including a ditch. Passing the ditch exposes vehicle occupants to potentially strong impact that may be more harmful than hitting a cable barrier. Also, the impact angle is generally larger for far-side cable barrier collisions. From the viewpoint of reducing the injury probability of vehicle occupants, installing two cable barriers - one on each side of the median - may be beneficial.

It was also interesting to see how median guardrail collisions differ from the roadside guardrail collisions in their risk of injury. The odds of injury from hitting a roadside guardrail were 49% (0.21/0.41=0.51) lower than the odds for a median guardrail. Higher speeds on divided roadways and majority of vehicles occupied only by a driver increased the risk of personal injury if a vehicle departed the roadway to the left rather than the right. The same comment applies to other types of evaluated barriers. In other words, concrete walls and cable barriers installed on the roadside may perform better than the ones estimated with the model.

Although the above conclusions provide useful insights on quantifying and comparing the injury risk of different types of barriers, the actual field decision on barrier selection should take into account other important factors, such as local traffic characteristics (AADT and heavy vehicle percentage), crash history, barrier repair and maintenance, barrier cost-effectiveness, compatibility with adjacent barriers, etc. For instance, concrete barriers may be a better alternative in areas where barriers are frequently struck by vehicles given the fact that guardrails and cable barriers do not often remain effective after vehicles crash into them while concrete barriers do.

Cross-median events vs. barrier collision events

As expected, cross-median events were shown to be associated with the highest injury risk, particularly for cross-median head-on events. Hitting a median barrier wall, median guardrail, nearside median cable barrier, and far-side cable barrier lowered the odds of injury by 77%, 78%, 97%, and 86% respectively, compared with cross-median head-on events. For cross-median non-head-on events, since their performance was similar as non-cross-median high-risk events, the odds of injury compared to barrier events can be obtained in Section 7.4.1.

Vehicle redirection events vs. barrier collision events

Given that the vehicle redirection event can be increased by the use of barriers, their injury risk is important in justifying the use of barriers. Compared to vehicle redirection events, striking a median barrier wall and a median guardrail increased the odds of injury by 24% and 21% respectively, whereas striking a nearside and a far-side median cable barrier lowered the odds of injury by 85% and 41% respectively, which indicates generally the redirection events are not a concern of using barriers since they are more forgiving than collisions with non-flexible barriers.

Non-cross-median moderate-risk events vs. barrier collision events

Striking a near-side median cable barrier had an odds of injury lower by 74%, when compared to a non-cross-median moderate-risk event such as crossing a ditch or hitting a sign post. On the other hand, striking a median concrete barrier wall, a median guardrail, or a far-side median cable barrier may expose the vehicle occupants to a similar or larger risk of injury than a moderate hazard event. These findings indicate that concrete barriers and guardrails should not be used to treat non-cross-median moderate-risk hazards whereas cable barriers may be beneficial.

7.4.2 Other Factors Influencing Injury Risk

The results from past studies indicated that the relative propensity to severe injury for passengers compared with drivers varied with the seat position (i.e., front passengers or rear seat passengers). Hutchinson (1986) found that front seat passengers were more likely to experience severe injury than drivers in non-overturning crashes. Eluru et al. (2010) stated that front seat passengers had a higher propensity to be severely injured than drivers when the driver was male. Rear seat passengers, on the other hand, were found to be associated with lower risk of injury or death (Smith and Cummings, 2004; Mayrose and Priya, 2008). The current study's results indicate that drivers were more likely to be injured than non-driver occupants (odds ratio 1.30). The available data did not allow determining the seating position in a vehicle for non-driver occupants. It seems that the advantage of sitting in a rear seat exceeded on average the disadvantage of sitting in the passenger front seat. Drivers 55 and over were exposed to a higher risk of injury upon impact with a fixed object, which could be attributed to the difference in physical conditions for that age group but also may be due to the possible bias of police officers who fill out the crash form.

Other interesting results in Table 7.3 include the effect of different types of vehicles. The reference category for vehicle type was the passenger car, SUV, pickup, van, recreational vehicle, or other unknown types. Heavy vehicles were found to be associated with lower injury risk possibly due to their different physical profile and mechanical components. The positive signs of the coefficients for motorcycles indicated that riding a motorcycle increases the probability of involvement in a severe vehicle crash compared with the vehicles of the reference category. This was expected due to the much higher exposure of motorcyclists to injury.

The interaction terms between the barrier collision event category and the vehicle type were tested to detect the difference in injury risk between different vehicle types hitting the same type of barrier with the same offset. No significant differences were found. In some cases, particularly for motorcycles, the lack of statistical significance could be explained by the small number of studied vehicle type and barrier type combinations. The insignificant interaction results for other vehicle and barrier types may indicate that these differences indeed may not be that large.

The roadway surface conditions were found to be significant in this study. Dry pavement conditions were used as a reference category. The poor condition category was a combination of the subcategories of mud, snow, slush, ice, water, and loose material on the road, all of which were found to have similar effects on the injury outcome. As indicated by the coefficients, driving on poor and wet road surfaces decreased the probability of injury, which might be explained by motorists tending to maintain lower speeds in undesirable road surface conditions.

7.4.3 Random Effects and Goodness-of-Fit

The random effects for both the segment pairs and the vehicles were significant based on their respective parameter estimate and standard error, although the evidence for segment pair random effects was not strong enough to pass a conventional 10% or 5% significance test. Additionally, the former was shown to be smaller than the latter, indicating that there was more heterogeneity unexplained by the vehicle-specific variables than the segment-specific variables. To test the effect of a large number of single-occupant vehicles in the sample, a model was estimated based on a subset of observations that included only multi-occupant vehicles. It was found that the random effect of a vehicle was stronger than in the original sample. Thus, more efforts should be devoted in future studies to incorporate vehicle-related variables. As far as the missing vehicle-specific information in this study, the seating position of the vehicle occupant is a major one. Other unobserved contributing factors for larger vehicle random effects might include vehicle mechanical condition, driver's control of the vehicle, etc.

In terms of the goodness-of-fit, the ratio of the generalized chi-square statistic and its degrees of freedom measured the residual variability in the marginal distribution of the data. As shown in Table 7.3, this value was 0.55, indicating that the variability of the crash data was properly handled by the proposed model.

7.4.4 Variables Found Insignificant

Some important variables, such as the weather, speed limit, urban indicator, rumble strip indicator, AADT, and roadside hazard rating index, were not found to be significant. The influence of weather was captured by the roadway surface condition, which was highly significant in our analysis. Although the rumble strip is believed to be effective in preventing crash occurrence, as reported by multiple past studies, it seems the severity was not significantly affected by the rumble strip for crashes that were not prevented by rumble strips. Since the majority of the crashes in this study were single-vehicle crashes, whose severity outcomes have little to do with interactions with other vehicles in most cases, the influence of AADT was not found to be significant. For the roadside hazard rating index, its insignificant results could be explained by its high correlation with the roadside objects, for which most of their information was captured by the event category. The insignificant results of speed limit may be related to the small variability of speed limit in this study as the majority of the analyzed crashes occurred on interstate roads or high-speed rural roads.

There are some variables that are expected to be important in crash injury analysis but were not included due to the lack of relevant data. Although this study modeled the probability of injury based on all vehicle occupants where passengers shared a lot of variables with the driver (e.g., the event categories, the vehicle type, the roadway surface condition, etc.), the demographic information and safety device usage (e.g., belted vs.

unbelted, airbag deployed vs. airbag not deployed) for uninjured passengers were not required to be provided by the police and thus are not available in this analysis.

7.5 Chapter Summary

The injury analysis in this chapter investigated the factors that affect a vehicle occupant's risk of injury. The injury here refers to the injury outcome of fatal, incapacitating, and non-incapacitating. Important factors were the hazardous events that included hitting barriers. Those hazardous events were classified into several categories:

- cross-median head-on event
- cross-median non-head-on event
- vehicle redirected and hit another vehicle event
- median concrete barrier wall collision
- median guardrail (face) collision
- nearside median cable barrier collision (offset 30 feet or less to the travelled way)
- far-side median cable barrier collision (offset more than 30 feet to the travelled way)
- roadside guardrail collision
- non-cross-median high-risk event (e.g. rollover or hitting a sturdy fixed object)
- non-cross-median moderate-risk event (e.g. hitting a weak object, running over a ditch, etc.)

A total of 3,299 vehicle occupants in 2,049 barrier-relevant crashes that occurred between 2003 and 2012 on 732 pair-matched homogeneous barrier and non-barrier segments were analyzed. Information on the event category, traffic conditions, vehicles, occupants, weather, road geometric characteristics, and roadside hazards were linked to each involved vehicle occupant. A binary logistic regression model with mixed effects was established to estimate the effect of event categories and other factors on crash injury outcomes for all vehicle occupants. The developed model could be used to prevent an occupant's risk of injury under a given event category.

The results indicated that using pairs of adjacent segments that were different only by the presence of a barrier was beneficial. Furthermore, the random effects for vehicles indicated strong unknown common factors associated with individual vehicles. It was found that, with the data available for this study, the unexplained heterogeneity across vehicles was much larger than that across matched segment pairs.

The modeling results revealed that colliding with any studied type of median barrier, regardless of the offset, reduced the probability of injury when compared to crossing the median or colliding with a high-risk roadside object. The injury risk reduction (the barrier's forgiveness) varied strongly across the barrier types and their offsets. Compared with a cross-median head-on event/ cross-median non-head-on event/ non-cross-median high-risk event, the odds of injury were reduced by 77%/58%/58% for striking a median concrete barrier wall, by 78%/59%/59% for striking a median guardrail face, by 97%/95%/95% for striking a near-side median cable barrier, and by 86%/80%/80% for striking a median far-side cable barrier. Compared with a non-cross-median high-risk event, the odds of injury were reduced by 79% for striking a roadside guardrail.

Comparing the safety performance of barriers is important where they can be used alternatively. This study found that the odds of injury when striking a median guardrail were nearly the same as the odds of injury when striking a median concrete barrier wall. For comparisons between median cable barriers and median guardrails, hitting a nearside cable barrier and far-side cable barrier is associated with lower odds of injury by 88% and 51% respectively, when compared to hitting a guardrail. In light of these results, installing median cable barriers on both sides of the median to reduce their lateral offset may be beneficial for safety. Life-cycle cost analysis might help if this practice is justified. The study also found that the odds of injury from hitting a roadside guardrail were 49% lower than the odds for a median guardrail.

Other safety factors included in the study were whether the vehicle occupant was the driver, the driver age, the vehicle type, and the road surface condition. Future research should consider using more precise measurements of injuries. The subtle impact of barriers on crash severity may be difficult to estimate if the data collected on the scene are the only injury severity data available. Access to hospital injury evaluations performed by medical professionals could be beneficial to more accurately determining crash severity (Tarko et al., 2010). Recent methodological developments in adjusting for selectivity bias also could be used (Tarko and Azam, 2011).

CHAPTER 8. EXAMPLE IMPLEMENTATION OF THE MODELS

This chapter presents example statistical simulation that utilizes the three models developed in this study. The overall safety performance of barriers is evaluated by comparing the crash costs estimated for barrier and non-barrier scenarios.

8.1 Introduction

In this study, the overall safety performance for a studied median and roadside scenario was represented by crash costs. The crash cost estimation involved three components: 1) the crash frequency, 2) the event probability, and 3) the risk and severity of the injury (including fatality). Each individual component was estimated utilizing the developed corresponding models discussed in Chapters 5, 6, and 7. In this chapter, the results of the statistical simulation for each studied scenario on each collected segment to obtain these three values are presented, which are then combined to obtain the crash costs of the scenario. The crash cost estimation was conducted based on the KABCO scale (K: fatality, A: incapacitating injury, B: non-incapacitating injury, C: possible injury, and O: property-damage-only) and average comprehensive costs per injured person suggested by National Safety Council (2011).

Crash cost estimation is particularly important in the barrier usage decision-making process. With the estimated crash cost numbers or the procedures developed in this study, highway agencies can obtain the safety benefits of a barrier scenario (design scenario) of interest by deducting the crash costs under this scenario from the crash costs under the existing scenario (base scenario). A cost-effectiveness analysis then can be conducted by comparing the annual safety benefits with the annualized capital, maintenance, and repair costs of barriers.

The objective of this chapter therefore is to present the statistical simulation procedure and results for 1) crash costs estimation under different median and roadside scenarios (including barrier and non-barrier) and 2) overall crash costs comparison across different scenarios.

8.2 Median and Roadside Scenarios

A total of 18 studied median and roadside scenarios were introduced in Section 3.2.

Six median scenarios were identified as follows:

- M_NB_Nar: median 50 feet or narrower and no median barrier.
- M_NB_Wide: median wider than 50 feet and no median barrier.
- M_BW: median concrete barrier ball (in the center of a narrow median).
- M_GR: median guardrail (in the center of a median or at the nearside edge)
- M_CB_Near: nearside median cable barrier (with a lateral clearance 30 feet or less to the travelled way).
- M_CB_Far: far-side median cable barrier (with a lateral clearance more than 30 feet to the travelled way).

Three roadside scenarios were identified as follows:

- S_GR: roadside guardrail.
- S_NB_Low: no guardrail, roadside hazard rating 1 or 2.
- S_NB_High: no guardrail, roadside hazard rating from 3 to 7.

8.3 Adjustments Due to Lack or Infrequency of Data

Since the developed models were estimated based on the data collected in this study, the infrequency or lack of certain data in the sample did not allow the inclusion of infrequent cases. Therefore, for the purpose of illustration, model outputs had to be adjusted in order to make the crash cost comparison possible.

Adjustment on the lack of cross-median events

The data collected in this study did not represent cross-median crashes on segments with any type of median barrier installed. The models developed based on the data predict no cross-median crashes on segments with median barriers. Thus, the modeling results could lead to overestimation of the effectiveness of median barriers. Based on a review of the use of median cable barriers by different states conducted by a previous study (Ray et al., 2009), 100% reduction in cross-median crashes experienced by some states after the installation of median cable barriers was due to the short history of their use. They stated that their reduction rate due to cable barriers was generally closer to 95%. A recent study that investigated the in-service performance of both median cable barrier and median guardrails in Florida reported that cross-median crashes were reduced by 97.4% for median cable barriers and by 98.3% for median guardrails (Alluri et al., 2012a, 2012b).

Based on the findings of previous studies, the following adjustment was made. We assumed that 5% of the predicted collisions with median cable barriers and guardrails led to cross-median crashes. Specifically, 1% of them were cross-median head-on crashes and 4% of them were cross-median non-head-on crashes. The ratio between head-on and non-head-on crashes corresponds to the ratio observed in our data from non-median barrier segments (23 for head-on crashes and 88 for non-head-on crashes). For median concrete barriers, we assumed cross-median crashes were eliminated based on their performance in a previous study in Indiana (Tarko et al., 2008).

Adjustments on the infrequency of severe injuries

The infrequency of severe injuries (fatal and incapacitating) did not allow us to develop multiple discrete outcome models such as multinomial logit or ordered probit models, to distinguish the severe injury outcomes from the non-severe injury outcomes. Collapsing the original multiple injury levels into binary categories avoided the concern of model validity that would be experienced using multiple outcome models; however, there were concerns instead about the practical use of the models, which was the loss of information in the internal split of original categories.

The developed injury model (binary logit model with mixed effects) can predict only the binary outcomes of injury (KAB) or no injury (CO). Under the framework of binary logit models, a fatal crash is weighted equal to a non-incapacitating crash since they both belong to the same collapsed category, which is injury. However, common sense as well as the published economic numbers tells us they are very different. The crash costs from more severe hazardous events would be underestimated if the injury analysis is limited to the predicted binary outcomes and does not consider the internal split within those collapsed categories. Thus, the predicted binary outcomes need to be further classified.

The proposed adjustment was as follows: from the model-predicted number of injured occupants (KAB occupants) and uninjured occupants (CO occupants) under a given event, we further assign them to the original injury levels (i.e. K, A, B, C, or O) based on their corresponding proportions for the given event shown in our data. With this adjustment, the predicted occupants were eventually classified according to the five levels in KABCO scale. We later converted all the occupants to monetary losses and aggregated them to obtain the total crash costs.

8.4 Simulation Procedure

As previously mentioned, the three developed models with necessary supplements were used to estimate the crash costs. Figure 8.1 shows the structure of the procedure.

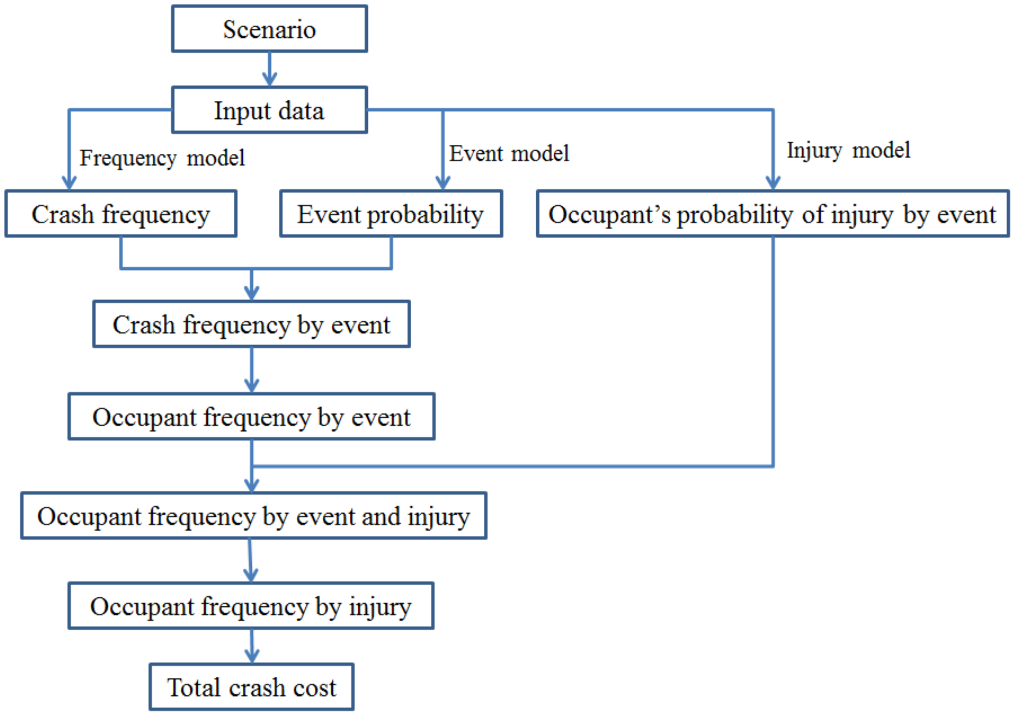


Figure 8.1 Flow Chart of the Structure of the Statistical Simulation

The major steps for calculating the predicted annual crash costs for a given directional roadway segment under a median and roadside scenario of interest are as follows:

1) Choose a scenario of interest.
2) Collect the input data.
3) Calculate the annual crash frequency.
4) Calculate the crash event probability.
5) Calculate the annual crash frequency by event category.
6) Calculate the annual number of occupants by event category.
7) Calculate occupant's probability of each injury outcome by event category.
8) Calculate the annual number of occupants by event category and injury level.
9) Calculate the annual number of occupants by injury level.
10) Calculate the annual total crash costs.

The details of the step-by-step procedure for statistical simulation are provided as below.

Step1: Choose a scenario of interest.

Choose a median and roadside scenario of interest for the given directional roadway segment under the existing roadway and roadside characteristics.

Step 2: Collect the input data.

The input data consist of the directional AADT, segment length, roadway functional class, speed limit, horizontal curve, and urban/rural area. The corresponding scenario information, such as the barrier type and offset selected in Step 1, are inputs as well. For the same segment under different scenarios, all the information is kept the same, except the information about the scenario.

Some steps may require input data that agencies cannot easily assess, which is particularly the case for information that is not about segment, such as the vehicle and occupant characteristics. However, that information tends to be stable over time and space and unaffected by roadway segment characteristics, and we therefore determined suggested values for that information based on the characteristics shown in the observed sample, which are introduced in the relevant following steps.

Step 3: Calculate the annual crash frequency.

Enter the input data into the developed frequency model in Chapter 5 and calculate the predicted annual total number of barrier-relevant crashes for the segment using the following equation:

$$
\begin{aligned}
C = AADT^{0.6060} \times SegL^{1.0083} \\
\times \exp\{-7.9597 + 0.9854 \times M\_BW + 0.5888 \times M\_GR + 0.2724 \times M\_CB \\
+ 0.9443 \times MCBTR + 1.6622 \times FrGE65 + 0.9404 \times FrLE60\}
\end{aligned}
\tag{8.1}
$$

where,

C	= predicted annual barrier-relevant crash frequency in one direction;
$AADT$	= directional annual average daily traffic in veh/day;
$SegL$	= segment length in miles;
M_BW	= indicator for median concrete barrier wall; 1 if the scenario has a median barrier wall and 0 if not;
M_GR	= indicator for median guardrail; 1 if the scenario has a median guardrail and 0 if not;
M_CB	= indicator for median cable barrier; 1 if the scenario has a median cable barrier and 0 if not;
$MCBTR$	= indicator for median cable barrier on a right curve; 1 if yes and 0 if no;
$FrGE65$	= indicator for freeway with speed limit greater than or equal to 65 mph; 1 if yes and 0 if no;
$FrLE60$	= indicator for freeway with speed limit less than or equal to 60; 1 if yes and 0 if no.

<u>Step 4: Calculate the crash event probability.</u>

This step calculates the probability of a barrier-relevant crash resulting in different event categories using the developed event model in Chapter 6. There are seven possible event categories in Chapter 6: 1) cross-median head-on event (event XH), 2) cross-median non-head-on event (event XNH), 3) vehicle redirected and collided with another vehicle event (event RHV), 4) non-cross-median high-risk event (event HR), 5) non-cross-median moderate-risk event (event MR), 6) median barrier collision event (event MB), and 7) roadside barrier collision event (event SB).

First, identify the conditional event set for the selected scenario from the following:

- Both median and roadside barriers installed: {RHV, MB, SB, HR, MR}
- Only median barriers installed: {RHV, MB, HR, MR}
- Only roadside barriers installed: {XH, XNH, RHV, SB, HR, MR}
- No barriers installed: {XH, XNH, RHV, HR, MR}

Second, enter the input data into the expected propensity function for each event in the conditional event set. The expected propensity functions are:

$$\overline{U}_{XH} = -1.636 - 1.618 \times M\_NB\_Wide + 0.776 \times R\_GR \tag{8.2}$$

$$\overline{U}_{XNH} = -0.621 - 1.099 \times M\_NB\_Wide \tag{8.3}$$

$$\begin{aligned}\overline{U}_{RHV} = &-4.066 + 1.893 \times M\_BW + 2.288 \times M\_CB\_Near + 1.890 \times M\_GR \\ &+ 1.452 \times R\_GR + 0.563 \times URBAN\end{aligned} \tag{8.4}$$

$$\overline{U}_{HH} = 0 \tag{8.5}$$

$$\overline{U}_{MR} = -0.347 \times M\_NB\_Wide + 0.324 \times R\_NB\_Low \tag{8.6}$$

$$\overline{U}_{MB} = 1.325 - 0.727 \times M\_CB\_Far - 0.649 \times M\_GR + 0.613 \times R\_GR \tag{8.7}$$

$$\overline{U}_{SB} = 1.122 - 1.035 \times M\_NB\_Wide + 0.337 \times FrGE65 \tag{8.8}$$

where,

M_NB_Wide	= indicator variable for wide median with no barrier. 1 if the median scenario is a wide median (width > 50ft) with no barrier and 0 if not.
M_BW	= indicator variable for median concrete barrier. 1 if the median scenario is a median concrete barrier and 0 if not.
M_GR	= indicator variable for median guardrail. 1 if the median scenario is a median guardrail and 0 if not.

M_CB_Near	= indicator variable for nearside median cable barrier. 1 if the median scenario is a nearside cable barrier (offset ≤ 30ft) and 0 if not.
M_CB_Far	= indicator variable for far-side median cable barrier. 1 if the median scenario is a far-side cable barrier (offset > 30ft) and 0 if not.
R_NB_Low	= indicator variable for non-barrier roadside with low hazard rating. 1 if the roadside scenario is a non-barrier roadside with low hazard rating (1 or 2) and 0 if not.
R_GR	= indicator variable for roadside guardrail. 1 if the roadside scenario is a roadside guardrail and 0 if not.
$URBAN$	= indicator variable for urban area. 1 if the segment is in urban area and 0 if not.
$FrGE65$	= indicator for freeway with speed limit greater than or equal to 65 mph; 1 if yes and 0 if no.

Third, calculate the probability of each eligible event using the logit function. The j th eligible event is calculated as follows (subscript i is omitted):

$$P(E_j) = \frac{\exp(\overline{U}_j)}{\sum_{\forall j \in J} \exp(\overline{U}_j)} \tag{8.9}$$

Note that the denominator in Equation 8.9 is the summation of the exponentiated propensities for all the eligible event categories in the conditional event set. Also note that after U_{MB} is determined, it is necessary to clarify the type of median barrier to which it actually refers.

For example, assume the selected scenario is a near-side median cable barrier and no roadside barrier with a hazard rating less than or equal to 2. The eligible event set is {RHV, MB, HR, MR}. Then we calculate $\overline{U}_{RHV}$, $\overline{U}_{MB}$, $\overline{U}_{HR}$, and $\overline{U}_{MR}$; and finally we calculate $P(E_{RHV})$, $P(E_{MB})$, $P(E_{HR})$, and $P(E_{MR})$. For example, the probability of a median barrier collision is $P(E_{MB}) = \dfrac{\exp(\overline{U}_{MB})}{\exp(\overline{U}_{RHV}) + \exp(\overline{U}_{MB}) + \exp(\overline{U}_{HR}) + \exp(\overline{U}_{MR})}$.

According to the median type for the scenario, we can then conclude that the probability for a barrier relevant crash resulting in a near-side cable barrier collision is $P(E_{MB})$.

Step 5: Calculate the annual crash frequency by event category.

Based on the results from Steps 3 and 4, the model predicted crash frequency for j th available event category is calculated as:

$$C_j = C \times P(E_j) \tag{8.10}$$

If the scenario includes a median cable barrier or median guardrail, we then adjust the crash count obtained from the model to account for the fact that there is still a small chance of median crossover crashes on segments with median cable barriers and median guardrails as discussed in Section 8.3.

So if the scenario includes a median cable barrier or median guardrail, then the adjusted crash count for the median barrier collision is:

$$C_{MB}^{Adjusted} = 0.95 \times C_{MB} \tag{8.11}$$

The adjusted crash count for the cross-median head-on event is:

$$C_{XH}^{Adjusted} = 0.01 \times C_{MB} \tag{8.12}$$

The adjusted crash count for the cross-median non-head-on event is:

$$C_{XNH}^{Adjusted} = 0.04 \times C_{MB} \tag{8.13}$$

For the median guardrail scenarios, C_{MB} is the predicted crash count of median guardrail collisions. For the median cable barrier scenarios, C_{MB} in Equations 8.12 and

8.13 is the average of the predicted crash counts of near-side and far-side cable barrier collisions.

Step 6: Calculate the annual number of occupants by event category.

In this step, the average number of vehicle occupants involved in each crash is required. Based on the data collected for this study, the suggested values for the average number of vehicle occupants involved in each crash are:

- $occ_j = 1.557$ for single vehicle crashes (i.e. crashes with events XNH, MB, SB, HR, or MR)
- $occ_j = 3.100$ for multiple vehicle crashes (i.e. crashes with events XH or RHV)

Then we can calculate the annual total number of involved vehicle occupants for each crash event category as:

$$O_j = C_j \times occ_j \tag{8.14}$$

Step 7: Calculate occupant's probability of each injury outcome by event category.

This step uses the developed injury model in Chapter 7. The model requires input information for the vehicles and the occupants, which is not easy to access for agencies. Thus, we provide the suggested values based on the data collected for this study as follows:

- For driver/non-driver, the percentage is 0.6438/0.3562.
- For mature driver/non-mature driver, the percentage is 0.1370/0.8630.
- For truck/motorcycle/car and other, the percentage is 0.0828/0.0042/0.9140.
- For poor surface/wet surface/dry surface, the percentage is 0.4019/0.1579/0.4402.

The injury model is then run to obtain the occupants' probability of injury (KAB) and non-injury (CO) for each event category as shown in Table 8.1. P_j^{KAB} and P_j^{CO} denote the injury probability and non-injury probability for each occupant involved in j th event category, respectively.

Table 8.1 The Predicted Occupants' Injury and Non-Injury Probability by Event Category (Binary Logit Model)

Event categories	Injury outcomes		
	Injury (KAB)	Non-injury (CO)	Total
Non-cross-median high-risk event	30.27%	69.73%	100%
Median barrier wall collision	16.25%	83.75%	100%
Nearside median cable barrier collision	2.39%	97.61%	100%
Far-side median cable barrier collision	8.79%	91.21%	100%
Median guardrail (face) collision	15.96%	84.04%	100%
Non-cross-median moderate-risk event	8.24%	91.76%	100%
Vehicle redirected and hit another vehicle	13.64%	86.36%	100%
Roadside guardrail collision	9.18%	90.82%	100%
Cross-median head-on	43.04%	56.96%	100%
Cross-median non-head-on	30.15%	69.85%	100%

Table 8.2 The Share of Injury Level K, A, and B in the Collapsed Injury KAB by Event Category

Event categories	Injury outcomes within KAB			
	Fatal (K)	Incapacitating (A)	Non-incapacitating (B)	Total
Non-cross-median high-risk event	2.76%	11.66%	85.58%	100%
Median barrier wall collision	0%	7.14%	92.86%	100%
Nearside median cable barrier collision	0%	0%	100%	100%
Far-side median cable barrier collision	0%	0%	100%	100%
Median guardrail (face) collision	0%	9.52%	90.48%	100%
Non-cross-median moderate-risk event	0%	8%	92%	100%
Vehicle redirected and hit another vehicle	5%	5%	90%	100%
Roadside guardrail collision	0%	5%	95%	100%
Cross-median head-on	32.14%	14.29%	53.57%	100%
Cross-median non-head-on	2.13%	10.64%	87.23%	100%

Table 8.3 The Share of Injury Level C and O in the Collapsed Injury CO by Event Category

Event categories	Injury outcomes within CO		
	Possible injury (C)	Property damage only (O)	Total
Non-cross-median high-risk event	2.59%	97.41%	100%
Median barrier wall collision	1.47%	98.53%	100%
Nearside median cable barrier collision	1.06%	98.94%	100%
Far-side median cable barrier collision	0%	100%	100%
Median guardrail (face) collision	0%	100%	100%
Non-cross-median moderate-risk event	1.16%	98.84%	100%
Vehicle redirected and hit another vehicle	0%	100%	100%
Roadside guardrail collision	0.45%	99.55%	100%
Cross-median head-on	0%	100%	100%
Cross-median non-head-on	4.49%	95.51%	100%

As discussed in Section 8.3, from the predicted binary injury outcomes we further obtain the probability of each original injury level based on their respective share as shown from the data. Table 8.2 shows the share of fatal ($P_j^{K|KAB}$), incapacitating injury ($P_j^{A|KAB}$), and non-incapacitating injury ($P_j^{B|KAB}$) in the collapsed injury category for each event category. Table 8.3 shows the share of possible injury ($P_j^{C|CO}$) and property-damage-only ($P_j^{O|CO}$) in the collapsed non-injury category for each event category.

With the model-predicted collapsed injury outcome and the respective (relative) share of the original injury level in those collapsed categories, we can calculate the occupants' probability of i th injury level (i = K, A, B, C, O) involved in j th event category as follows:

$$P_j^i = P_j^{i|KAB} \times P_j^{KAB} \text{ for } i \text{ in K, A and B} \tag{8.15}$$

$$P_j^i = P_j^{i|CO} \times P_j^{CO} \text{ for } i \text{ in C and O} \tag{8.16}$$

<u>*Step 8: Calculate the annual number of occupants by event category and injury level.*</u>

Using the results from Steps 6 and 7, we can calculate the annual number of occupants for i th injury level under j th event category as follows:

$$O_j^i = O_j \times P_j^i \tag{8.17}$$

<u>*Step 9: Calculate the annual number of occupants by injury level.*</u>

The total number of occupants for i th injury outcome is obtained by aggregating across different event categories as follows:

$$O^i = \sum_{j=1}^{m} O_j^i \tag{8.18}$$

<u>*Step 10: Calculate the annual total crash costs.*</u>

The annual total crash costs are calculated as the sum of the individual costs for occupants classified at different injury levels. Table 4.2 provides the average comprehensive cost per person by injury level according to the National Safety Council (2011).

Thus, the annual total costs are calculated as:

$$CC = 4,459,000 \times O^K + 225,100 \times O^A + 57,400 \times O^B + 27,200 \times O^C + 2,400 \times O^O \tag{8.19}$$

We now have obtained the crash costs for the selected scenario in Step 1 for the given segment. Step 1 to Step 10 can be repeated until all the scenarios of interest have been analyzed. At the end of the process, the total costs for each scenario for each segment are available for further cost-effectiveness analysis.

8.5 Crash Cost Estimation Results

The simulation procedure detailed in the previous section would be particularly useful when a highway agency would like to obtain a high-resolution barrier performance prediction for a roadway segment of interest. The results obtained from the proposed procedure of this study could offer information specific to the roadway segment of interest. The focus of this section, however, was not on an individual segment but rather a general overview of the comparative performance of barriers in different median and roadside scenarios in Indiana. In other words, the focus was to investigate how the overall performance of barriers would change if a certain design scenario was used rather than the existing approach. This information could help decision-makers understand the complete effect of barriers at a higher level.

In this study, the overall safety performance of a barrier or non-barrier scenario was represented by the crash costs under the scenario. For each collected directional segment, we therefore tested all 18 median and roadside scenarios by running the aforementioned simulation procedure for each scenario. After we obtained the individual annual crash cost under each scenario for each segment, we summed them over all segments under each scenario and then divided the sum by the total length of all the segments. The obtained results were the average crash costs per mile per year on a typical directional roadway segment in Indiana and the monetary loss due to all barrier-relevant crashes.

Table 8.4 lists the total crash costs and individual event crash costs (in $1,000 per mile per year) for each studied scenario. The total crash costs are the sum of crash costs for all individual event categories. The corresponding crash frequency (in per mile per year) and the average cost per crash (in $1,000) are also provided.

Median scenarios: barrier vs. non-barrier

As Table 8.4 shows, the total crash costs for nearly all median barrier scenarios were substantially less than those for non-median barrier scenarios. Compared to non-median barrier scenarios, the total crash costs for cable barrier scenarios were roughly half of that for wide median scenarios and a quarter of that for narrow median scenarios. The total crash costs for concrete barrier scenarios and guardrail scenarios were slightly less than that for wide median non-barrier scenarios and roughly half of that for narrow median non-barrier scenarios. These comparisons justified the use of cable barriers in wide medians and concrete barriers and guardrails in narrow medians. The use of those barriers roughly cuts the crash costs in half.

The considerable difference between the median barrier and non-median barrier scenarios mainly were attributable to cross-median head-on events. Based on the adjustments we made to the median barriers' effectiveness in reducing cross-median events (see Section 8.3), the cross-median (head-on and non-head-on) crash costs were eliminated under the median concrete barrier scenarios. Even for other median barrier scenarios, the cross-median head-on crash costs were only around 10% of those for narrow median scenarios and around one third of those for wide median scenarios, which suggested that the major benefits of using median barriers are the elimination or reduction of cross-median head-on events.

Table 8.4 Scenarios' Crash Costs (in $1,000 per Mile per Year) by Event Category

Median Scenario	Roadside Scenario	Crash Costs by Event							Total Crash Costs	Total Crash Frequency	Cost Per Crash
		XH	XNH	RHV	MR	HR	MB	SB			
M_CB_Near	R_NB_High	7.98	1.33	3.08	1.57	11.73	2.69	0.00	28.38	0.72	39.30
M_CB_Near	R_NB_Low	7.39	1.23	2.90	2.03	11.02	2.53	0.00	27.11	0.72	37.55
M_CB_Near	R_GR	6.10	1.02	5.61	0.67	4.99	2.12	2.80	23.32	0.72	32.29
M_CB_Far	R_NB_High	7.98	1.33	0.49	2.43	18.22	3.63	0.00	34.07	0.72	47.18
M_CB_Far	R_NB_Low	7.39	1.23	0.44	3.06	16.57	3.30	0.00	31.99	0.72	44.30
M_CB_Far	R_GR	6.10	1.02	0.83	0.97	7.26	2.66	4.07	22.91	0.72	31.72
M_BW	R_NB_High	0.00	0.00	4.09	3.09	23.15	19.03	0.00	49.35	1.41	35.01
M_BW	R_NB_Low	0.00	0.00	3.84	4.01	21.74	17.87	0.00	47.46	1.41	33.67
M_BW	R_GR	0.00	0.00	7.51	1.33	9.95	15.10	5.59	39.48	1.41	28.01
M_GR	R_NB_High	9.09	1.52	3.94	2.99	22.39	9.23	0.00	49.17	0.95	51.86
M_GR	R_NB_Low	8.32	1.39	3.61	3.78	20.48	8.44	0.00	46.02	0.95	48.54
M_GR	R_GR	6.62	1.11	6.65	1.18	8.83	6.72	4.96	36.06	0.95	38.03
M_NB_Nar	R_NB_High	74.50	8.57	0.49	2.47	18.51	0.00	0.00	104.55	0.53	198.68
M_NB_Nar	R_NB_Low	65.41	7.53	0.43	3.00	16.25	0.00	0.00	92.63	0.53	176.03
M_NB_Nar	R_GR	61.56	3.26	0.81	0.94	7.04	0.00	3.95	77.56	0.53	147.39
M_NB_Wide	R_NB_High	20.90	4.04	0.70	2.47	26.20	0.00	0.00	54.31	0.53	103.21
M_NB_Wide	R_NB_Low	18.35	3.55	0.61	3.00	23.00	0.00	0.00	48.51	0.53	92.19
M_NB_Wide	R_GR	24.89	2.22	1.64	1.36	14.36	0.00	2.86	47.33	0.53	89.95

XH: cross-median head-on event
XNH: cross-median non-head-on event
RHV: redirected and hit another vehicle event
MB: median barrier collision event
SB: roadside barrier collision event
HR: non-cross-median high-risk event (e.g. rollover or hitting a sturdy fixed object)
MR: non-cross-median moderate-risk event (e.g. hitting a weak object, running over a ditch, etc)
M_NB_Nar: median 50 feet or narrower and no median barrier
M_NB_Wide: median wider than 50 feet and no median barrier
M_BW: median concrete barrier wall placed in the center of a narrow median
M_GR: median guardrail placed in the center of a median or at the nearside edge
M_CB_Near: median cable barrier with a lateral clearance 30 feet or less to the travelled way
M_CB_Far: median cable barrier with a lateral clearance more than 30 feet to the travelled way
R_GR: roadside guardrail
R_NB_Low: no guardrail, roadside hazard rating: 1 or 2
R_NB_High: no guardrail, roadside hazard rating from 3 to 7

Median scenarios: comparison among different median barriers

Among all the median barrier scenarios, nearside cable barriers were shown to be the most effective, followed by far-side cable barriers, guardrails, and concrete barriers. The crash costs of the latter two scenarios were about 50% more than those of the former two.

The difference in total crash costs between the nearside and far-side cable barrier scenarios was minor. Most of the crash costs for the cable barrier scenarios were attributable to non-cross-median high-risk events (e.g., rollover in a median), especially when the roadside had no barrier. It was interesting to note that, compared to the far-side cable barrier scenarios, the nearside scenarios experienced less non-cross-median high-risk event crash costs but more vehicle redirection crash costs.

The difference in total crash costs between the median concrete barrier scenarios and the guardrail scenarios was also minor. Although the median concrete barrier scenarios experienced twice as much barrier collision crash costs compared to median guardrail scenarios, their performance eventually evened out due to the elimination of the cross-median events experienced by the former.

Roadside scenarios: roadside guardrail vs. non-barrier roadside

For the roadside scenarios, roadside guardrail was shown to be associated with smaller total crash costs than the two non-barrier scenarios due mainly to its crash cost reduction in non-cross-median high-risk events. Although the crash costs for vehicle redirection events were higher for roadside guardrail scenarios, its increase was much less than the crash cost reduction in non-cross-median high-risk events.

Even though the comparison indicated that the use of roadside guardrail reduced crash costs, the reduction was not substantial, especially when compared to the use of median barriers. Generally, the use of roadside guardrail could result in roughly 20% to 30% crash cost reduction, indicating that the use of roadside guardrail probably should be justified from other aspects, such as liability concerns or the need for protection of valuable properties along the roadside.

Other characteristics associated with crash costs

From the values for total crash frequency across different scenarios, we can see that they only varied with the type of median barriers, which reflected the characteristics of the developed crash frequency model. The median concrete barrier scenarios had the highest crash frequency, followed by the median guardrail scenarios, and the median cable barrier scenarios. The cost per crash was calculated as the total crash costs divided by the total crash frequency. Non-median barrier scenarios had much higher values for the cost per crash due to much higher chances of cross-median events and lower number of total crashes.

8.6 Chapter Summary

This chapter assessed the overall performance of barrier and non-barrier median and roadside scenarios in terms of total crash costs due to barrier-relevant crashes. The total crash costs were composed of individual crash costs from seven event categories: cross-median head-on, cross-median non-head-on, vehicle redirected and collided with another vehicle, non-cross-median high-risk, non-cross-median moderate-risk, median barrier collision, and roadside barrier collision. The crash costs were estimated from three components: 1) the crash frequency, 2) the event probability, and 3) the risk and severity of the injury (including fatality).

A procedure based on statistical simulation was proposed to conduct cost estimation prediction based on the KABCO scale and the average comprehensive costs per injured person. The procedure used the developed crash frequency model, event model, and injury model in Chapters 5, 6, and 7, respectively, to estimate each component of crash costs. In the procedure, the model-predicted results were supplemented with certain practical adjustments as well as some information directly obtained from the collected data.

To obtain a general overview of the comparative performance of different barrier and non-barrier scenarios in Indiana, the 18 studied scenarios were assumed under each collected directional segment and were tested by running the aforementioned simulation procedure for each scenario.

The simulation results revealed that all of the median barriers were effective in reducing crash costs. Specifically, crash costs were roughly cut in half with either the use of cable barriers in wide medians or the use of concrete barriers and guardrails in narrow medians. The major benefits of using median barriers were the elimination or reduction of cross-median head-on events. Among all the median barriers, cable barriers were shown to be associated with 50% lower crash costs when compared to concrete barriers and guardrails. The better performance of median cable barriers was related to its smaller increase in crash frequency and less severe injury outcomes associated with cable barrier collisions. Nearside cable barriers were shown to be slightly better than far-side cable barriers, and concrete barriers were similar to guardrails.

The use of roadside guardrails also reduced the crash costs, but was not as effective as the use of median barriers. Generally, the use of a roadside guardrail resulted in roughly 20% to 30% crash cost reduction with the majority of the cost reduction due to the decrease in non-cross-median high-risk events.

CHAPTER 9. CLOSURE

9.1 Conclusions

Road barriers have been used as an effective countermeasure to prevent errant vehicles from exposure to vehicles from the opposite direction or roadside hazards. During the last several years, the expanded scope of the application of median barriers has provided highway agencies with more viable barrier alternatives. However, current guidelines and manuals have not quite kept up with the most recent use of cable barriers, and the practices of different states also vary; subsequently, in-service evaluation of the safety performance of barriers is suggested. The in-service evaluation would not only check how much the field performance differed from the crash tests but also would provide valuable information in the decision-making process.

This study investigated the in-service performance of three types of road barriers (concrete barriers, W-beam guardrails, and high-tension cable barriers) installed on divided roads in Indiana. A number of 18 barrier and non-barrier scenarios were identified and studied based on their on-field use in the median and along the roadside. The in-service performance of barriers is consisted of three components:

- The effect of barriers on the crash frequency (segment level)
- The effect of barriers on the probability of hazardous events (crash level)
- The effect of hazardous events on the probability of injury outcomes (occupant level)

Each component of a barrier's performance was processed by a developed statistical model; and statistical simulation was conducted for each studied barrier and non-barrier scenario to assess its overall safety performance in terms of crash costs by incorporating all the results from the individual models.

A negative binomial regression model was developed to estimate the number of crashes that occurred on directional roadway segments from 2008 to 2012. All three types of median barriers were found to increase the crash frequency compared to a median with no barriers. Median concrete barrier walls produced the largest increase in crash frequency, followed by median guardrails and median cable barriers. The coexistence of median cable barriers and horizontal curves to the right also increased the crash frequency. Roadside guardrails were not found to significantly change the crash frequency nor did the barrier offset.

This study developed a multinomial logit model with variable outcomes to estimate the effect of barriers on the probability of hazardous events. The relevant hazardous events were divided into several event categories as below:

- Cross-median head-on event
- Cross-median non-head-on event
- Vehicle redirected and collided with another vehicle event
- Median barrier collision event
- Roadside barrier collision event
- Non-cross-median high-risk event (e.g., rollover or hitting a sturdy fixed object)
- Non-cross-median moderate-risk event (e.g., hitting a weak object, running over a ditch, etc.)

The model identified roadway and roadside characteristics that affect the probability of a barrier relevant crash to fall into each considered event category. The modelling results indicated that crashes on wider median are less likely to result in a cross-median event. Since the collected data did not have cross-median (head-on and non-head-on) events that occurred on segments with a median barrier installed, this suggested median barriers are very effective in reducing or even eliminating cross-median events. The total elimination would have been hard to achieve if we had a larger sample size, as found in some studies. The modelling results also indicated that the more rigid and closer placed a median barrier, the more likely a crash would result in a median barrier collision or redirected vehicle event. For non-cross-median high-risk and non-cross-median moderate-risk events, they were shown to be effectively reduced by the use of roadside guardrails. Both median and roadside barriers were found to increase the probability of vehicle redirection events.

A binary logit model with mixed effects was developed to estimate the effect of hazardous events on the occupants' probability of injury (fatality, incapacitating injury, or non-incapacitating injury). The study found that colliding with any of the studied types of median barriers, regardless of the offset, reduced the probability of injury when compared to crossing the median or colliding with a high-risk roadside object. Among the collisions with different types of median and roadside barriers, near-side median cable barriers (offset equal to or smaller than 30 feet) performed best, followed by far-side median cable barriers, roadside guardrails, median guardrails, and median concrete barriers. The results on the random effects for vehicles and paired segments indicated that the unexplained heterogeneity across vehicles was much larger than that across matched segment pairs.

Statistical simulation was used to obtain the crash costs for each studied barrier and non-barrier scenario by applying the previously developed statistical models. It was found that crash costs were roughly cut in half with either the use of cable barriers in wide medians (median width larger than 50 feet) or the use of concrete barriers and guardrails in narrow medians (median width less than or equal to 50 feet). The major benefit of using median barriers was the elimination or reduction of cross-median head-on events. Among all the median barriers, cable barriers were shown to be associated with 50% lower crash costs compared to concrete barriers and guardrails. The superior performance of median cable barriers was related to its smaller increase in crash frequency and the less severe injury outcomes associated with cable barrier collisions. Nearside cable barriers were shown to perform slightly better than far-side cable barriers, and concrete barriers were similar to guardrails. The superior performance shown by nearside cable barriers relative to far-side cable barriers were due to the former's larger reduction in non-cross-median high-risk events such as vehicle rollovers in the median. The use of roadside guardrails also reduced the crash costs but was not as effective as median barriers. Generally, the use of a roadside guardrail resulted in roughly 20% to 30% crash cost reduction, the majority of which was the cost reduction due to the decrease in non-cross-median high-risk events.

Overall, the study found that median cable barriers exhibited overwhelmingly better overall safety performance over other types of barriers. They should be preferred over a concrete barrier wall or a guardrail where the local conditions allow. It is worth considering expanding their use beyond the current practice.

9.2 Contributions

This study analyzed the in-service safety performance of multiple types of barriers from multiple perspectives. It not only helped understand the tree of events associated with the use of barriers but also provided in-depth insight into the overall evaluation of different barrier and non-barrier alternatives.

This study made every effort to select only crashes that were relevant to the performance of barriers, which included crashes normally ignored by previous studies, such as vehicle redirection crashes. The crash screening process ensured that the performance evaluation was not under- or over-estimated.

This study analyzed the injury outcome and crash costs at the occupant level. It avoided the bias associated with the traditional crash-level analysis, which is particularly important in the study of barriers since the most important type of crash, cross-median head-on, generally involves more vehicle occupants than other types of crash.

This study developed statistical models and identified factors that significantly affect the crash frequency, the event probability, and the occupants' injury outcomes. The crash event probability was seldom modelled in previous studies but was found important in the performance evaluation of barriers. These models can assist highway agencies in identifying the proper countermeasures to address the factors associated with negative impacts on traffic safety.

This study provided a practical procedure to predict the crash costs for different barrier and non-barrier scenarios. The procedure allows testing multiple viable scenarios based on the characteristics of the roadway segment at hand and then selecting the option with the highest safety benefits.

This study analyzed the contribution of different hazardous events to the total crash costs, which can help identify the primary crash cost source. It is useful particularly when the budget for countermeasures is limited.

The developed models and procedures can be used to obtain crash modification factors or crash cost modification factors, which would benefit the project screening process.

9.3 Future Study

A future study could include a life-cycle cost-effective analysis with consideration of the costs of the installation, maintenance, and repair of different barriers, which vary considerably across barrier types. Concrete barriers have the highest installation cost but very little maintenance and repair cost. Cable barriers have much lower installation costs, but repairs after a crash are very common. Thus, a life-cycle cost-effectiveness analysis would be beneficial in the final justification of the use of a certain barrier.

Future research could investigate expanding the use of cable barriers. This study concluded that nearside cable barriers performed better than far-side cable barriers. It would be interesting to see if placing cable barriers on both sides of the median would be more beneficial. The possible use of cable barriers on narrower medians or on roadsides is also worth investigating.

The infrequency of fatal and incapacitating crashes limited this study to using a binary logit model, which only can predict whether or not an occupant is injured. Future research should increase the sample size or use a different injury scale, such as the Main Abbreviated Injury Scale (MAIS). Compared to the KABCO scale used in this study, which is biased toward the occupants' conditions at the crash scene, the MAIS scale is believed to more accurately reflect the actual injuries sustained by the crash vehicle occupants. With more observations for each injury level available, multiple outcome models, such as multinomial logit models, ordered logit/probit models, and nested logit models, could be used to distinguish severe injury from non-severe injury.

Advanced models, such as random parameter models, Bayesian networks, etc., which recently have been widely applied in modeling crash data and have demonstrated better performance than traditional models, also could provide more insight into the effect of barriers.

REFERENCES

AASHTO. (2009). *Manual for assessing safety hardware (MASH).* Washington, D.C.: American Association of State Highway and Transportation Officials.

AASHTO. (2010). *Highway Safety Manual.* American Association of State Highways and Transportation Officials, Washington, D.C. .

AASHTO. (2011). *Roadside Design Guide.* Washington D.C.

Abdel-Aty, M., & Keller, J. (2005). Exploring the overall and specific crash severity levels at signalized intersections. *Accident Analysis & Prevention, 37*(3), 417-425.

Abdelwahab, H. T., & Abdel-Aty, M. A. (2001). Development of artificial neural network models to predict driver injury severity in traffic accidents at signalized intersections. *Transportation Research Record: Journal of the Transportation Research Board, 1746*, 6-13.

Alluri, P., Haleem, K., & Gan, A. (2012a). *In-service performance evaluation (ISPE) for G4 (1S) type of strong-post w-beam guardrail system and cable median barrier: volume I.* Florida DOT.

Alluri, P., Haleem, K., & Gan, A. (2012b). *In-service performance evaluation (ISPE) for G4 (1S) type of strong-post w-beam guardrail system and cable median barrier: volume II.* Florida DOT.

Anastasopoulos, P. C., & Mannering, F. L. (2009). A note on modeling vehicle accident frequencies with random-parameters count models. *Accident Analysis & Prevention, 41*(1), 153-159.

Anastasopoulos, P. C., & Mannering, F. L. (2011). An empirical assessment of fixed and random parameter logit models using crash- and non-crash-specific injury data. *Accident Analysis & Prevention, 43*(3), 1140-1147.

Anastasopoulos, P. C., Mannering, F. L., Shankar, V. N., & Haddock, J. E. (2012). A study of factors affecting highway accident rates using the random-parameters tobit model. *Accident Analysis & Prevention, 45*(1), 628–633.

Carson, J., & Mannering, F. (2001). The effect of ice warning signs on ice-accident frequencies and severities. *Accident Analysis & Prevention, 33*(1), 99-109.

Chang, L.-Y. (2005). Analysis of freeway accident frequencies: Negative binomial regression versus artificial neural network. *Safety Science, 43*(8), 541-557.

Chen, E., & Tarko, A. P. (2014). Modeling safety of highway work zones with random parameters and random effects models. *Analytic Methods in Accident Research, 1*, 86–95.

Cheng, L., Geedipally, S. R., & Lord, D. (2013). The Poisson–Weibull generalized linear model for analyzing motor vehicle crash data. *Safety Science, 54*, 38-42.

Chimba, D., & Sando, T. (2009). The prediction of highway traffic accident injury severity. *Advances in Transportation Studies, 19*(A), 17-26.

Chimba, D., Emaasit, D., Allen, S., Hurst, B., & Nelson, M. (2014). Factors affecting median cable barrier crash frequency: new insights. *Journal of Transportation Safety & Security, 6*(1), 62-77.

Chin, H. C., & Quddus, M. A. (2003). Applying the random effect negative binomial model to examine traffic accident occurrence at signalized intersections. *Accident Analysis & Prevention, 35*(2), 253–259.

Chitturi, M. V., Ooms, A. W., Bill, A. R., & Noyce, D. A. (2011). Injury outcomes and costs for cross-median and median barrier crashes. *Journal of Safety Research, 42* (2), 87-92.

Daniello, A., & Gabler, H. C. (2011a). Effect of barrier type on injury severity in motorcycle-to-barrier collisions in North Carolina, Texas, and New Jersey. *Transportation Research Record: Journal of the Transportation Research Board*, *2262*, 144-151.

Daniello, A., & Gabler, H. C. (2011b). Fatality risk in motorcycle collisions with roadside objects in the United States. *Accident Analysis and Prevention, 43*(3), 1167-1170.

Donnell, E. T., & Mason, J. M. (2006a). Methodology to develop median barrier warrant criteria. *Journal of Transportation Engineering, 132*(4), 269-281.

Donnell, E. T., & Mason, J. M. (2006b). Predicting the frequency of median barrier crashes on Pennsylvania interstate highways. *Accident Analysis and Prevention, 38*(3), 590–599.

Eluru, N., Bagheri, M., Miranda-Moreno, L. F., & Fu, L. (2012). A latent class modeling approach for identifying vehicle driver injury severity factors at highway-railway crossings. *Accident Analysis & Prevention, 47*, 119-127.

Eluru, N., Paleti, R., Pendyala, R. M., & Bhat, C. R. (2010). Modeling injury severity of multiple occupants of vehicles: copula-based multivariate approach. *Transportation Research Record: Journal of the Transportation Research Board, 2165*, 1-11.

Geedipally, S. R., Lord, D., & Dhavala, S. S. (2012). The negative binomial-Lindley generalized linear model: Characteristics and application using crash data. *Accident Analysis & Prevention, 45*, 258-265.

Greene, W. H. (2007). *NLOGIT (Version 4.0): Student Reference Guide.* NY.

Holdridge, J. M., Shankar, V. N., & Ulfarsson, G. F. (2005). The crash severity impacts of fixed roadside objects. *Journal of Safety Research, 36*, 139-147.

Hu, W., & Donnell, E. T. (2010). Median barrier crash severity: Some new insights. *Accident Analysis and Prevention, 42*(6), 1697-1704.

Hunter, W. W., Stewart, J. R., Eccles, K. A., Huang, H. F., Council, F. M., & Harkey, D. L. (2001). Three-strand cable median barrier in North Carolina. *Transportation Research Record: Journal of the Transportation Research Board, 1743*, 97-103.

Hutchinson, T. (1986). Statistical modelling of injury severity, with special reference to driver and front seat passenger in single-vehicle crashes. *Accident Analysis & Prevention, 18*(2), 157-167.

Indiana DOT. (2013). Indiana Design Manual.

Jama, H. H., Grzebieta, R. H., Friswell, R., & McIntosh, A. S. (2011). Characteristics of fatal motorcycle crashes into roadside safety barriers in Australia and New Zealand. *Accident Analysis and Prevention, 43*(3), 652-660.

Khattak, A. J., Council, F. M., & Kantor, P. (1998). The role of adverse weather in key crash types on limited access roadways: implications of advanced weather systems. *Transportation Research Record, 1621*, 10-19.

Khazraee, S. H., Sáez-Castillo, A. J., Geedipally, S. R., & Lord, D. (2014). Application of the hyper-Poisson generalized linear model for analyzing motor vehicle crashes. *Risk Analysis*, Forthcoming.

Kockelman, K. M., & Kweon, Y.-J. (2002). Driver injury severity: an application of ordered probit models. *Accident Analysis & Prevention, 34*(3), 313-321.

Lapparent, M. d. (2008). Willingness to use safety belt and levels of injury in car accidents. *Accident Analysis & Prevention, 40*(3), 1023-1032.

Lee, C., & Abdel-Aty, M. (2008). Presence of passengers: Does it increase or reduce driver's crash potential? *Accident Analysis & Prevention, 40*(5), 1703-1712.

Lee, J., & Mannering, F. (2002). Impact of roadside features on the frequency and severity of run-off-roadway accidents: an empirical analysis. *Accident Analysis and Prevention, 34*(2), 149-161.

Li, X., Lord, D., Zhang, Y., & Xie, Y. (2008). Predicting motor vehicle crashes using support vector machine models. *Accident Analysis & Prevention, 40*(4), 1611-1618.

Lord, D., & Mannering, F. (2010). The statistical analysis of crash-frequency data: A review and assessment of methodological alternatives. *Transportation Research Part A: Policy and Practice, 44*(5), 291-305.

Lord, D., Geedipally, S. R., & Guikema, S. D. (2010). Extension of the application of conway-maxwell-poisson models: Analyzing traffic crash data exhibiting underdispersion. *Risk Analysis, 30*(8), 1268-1276.

Lord, D., Guikema, S. D., & Geedipally, S. R. (2008). Application of the Conway-Maxwell-Poisson generalized linear model for analyzing motor vehicle crashes. *Accident Analysis & Prevention, 40*(3), 1123-1134.

Lord, D., Washington, S. P., & Ivan, J. N. (2005). Poisson, Poisson-gamma and zero-inflated regression models of motor vehicle crashes: balancing statistical fit and theory. *Accident Analysis & Prevention, 37*(1), 35-46.

Lord, D., Washington, S., & Ivan, J. N. (2007). Further notes on the application of zero-inflated models in highway safety. *Accident Analysis & Prevention, 39*(1), 53-57.

Ma, J., Kockelman, K. M., & Damien, P. (2008). A multivariate Poisson-lognormal regression model for prediction of crash counts by severity, using Bayesian methods. *Accident Analysis & Prevention, 40*(3), 964–975.

Malyshkina, N. V., & Mannering, F. (2008). Effect of increases in speed limits on severities of injuries in accidents. *Transportation Research Record: Journal of the Transportation Research Board, 2083*, 122-127.

Malyshkina, N. V., & Mannering, F. L. (2009). Markov switching multinomial logit model: An application to accident-injury severities. *Accident Analysis & Prevention, 41*(4), 829–838.

Malyshkina, N. V., & Mannering, F. L. (2010). Zero-state Markov switching count-data models: An empirical assessment. *Accident Analysis & Prevention, 42*(1), 122-130.

Mannering, F. L., & Bhat, C. R. (2014). Analytic methods in accident research: Methodological frontier and future directions. *Analytic Methods in Accident Research, 1*, 1-22.

Martin, J.-L., Mintsa-Eya, C., & Goubel, C. (2013). Long-term analysis of the impact of longitudinal barriers on motorway safety. *Accident Analysis and Prevention, 59*, 443-451.

Mayrose, J., & Priya, A. (2008). The safest seat: Effect of seating position on occupant mortality. *Journal of Safety Research, 39*, 433-436.

McFadden, D. (1981). *Econometric Models of Probabilistic Choice.* MIT Press.

Miaou, S.-P. (1994). The relationship between truck accidents and geometric design of road sections: Poisson versus negative binomial regressions. *Accident Analysis & Prevention, 26*(4), 471–482.

Miaou, S.-P., Bligh, R. P., & Lord, D. (2005). Developing guidelines for median barrier installation benefit–cost analysis with Texas data. *Transportation Research Record: Journal of the Transportation Research Board, 1904*, 3-19.

Milton, J. C., Shankar, V. N., & Mannering, F. L. (2008). Highway accident severities and the mixed logit model: an exploratory empirical analysis. *Accident Analysis and Prevention, 40*(1), 260-206.

Mitra, S., & Washington, S. (2012). On the significance of omitted variables in intersection crash modeling. *Accident Analysis & Prevention, 49*, 439-448.

Park, B.-J., & Lord, D. (2009). Application of finite mixture models for vehicle crash data analysis. *Accident Analysis & Prevention, 41*(4), 683-691.

Park, E. S., & Lord, D. (2007). Multivariate poisson–lognormal models for jointly modeling crash frequency by severity. *Transportation Research Record: Journal of the Transportation Research Board, 2019*, 1-6.

Poch, M., & Mannering, F. (1996). Negative binomial analysis of intersection-accident frequencies. *Journal of Transportation Engineering, 122*(2), 105-113.

Quddus, M. A., Wang, C., & Ison, S. G. (2010). Road traffic congestion and crash severity: Econometric analysis using ordered response models. *Journal of Transportation Engineering, 136*(5), 424-435.

Ray, M. H., Silvestri, C., Conron, C. E., & Mongiardini, M. (2009). Experience with cable median barriers in the united states: Design standards, policies, and performance. *Journal of Transportation Engineering, 135*(10), 711-720.

Ray, M., Weir, J., & Hopp, J. (2003). *In-service performance of traffic barriers.* Washington, D.C.: Transportation Research Board.

Ross, H. E., JR., D. L., & Zimmer, R. A. (1993). *Recommended procedures for the safety performance evaluation of highway features.* Washington, D.C.: Transportation Research Board.

Savolainen, P. T., Mannering, F. L., Lord, D., & Quddus, M. A. (2011). The statistical analysis of highway crash-injury severities: A review and assessment of methodological alternatives. *Accident Analysis and Prevention, 43*(5), 1666-1676.

Shankar, V. N., Albin, R. B., Milton, J. C., & Mannering, F. l. (1998). Evaluating median crossover likelihoods with clustered accident counts: An empirical inquiry using the random. *Transportation Research Record: Journal of the Transportation Research Board,1635*, 44-48.

Shankar, V., & Mannering, F. (1996). An exploratory multinomial logit analysis of single-vehicle motorcycle accident severity. *Journal of Safety Research, 27*(3), 183-194.

Shankar, V., Milton, J., & Mannering, F. (1997). Modeling accident frequencies as zero-altered probability processes: An empirical inquiry. *Accident Analysis & Prevention, 29*(6), 829-837.

Sheikh, N. M., Alberson, D. C., & Chatham, L. S. (2008). State of the practice of cable barrier systems. *Transportation Research Record: Journal of the Transportation Research Board, 2060*, 84–91.

Shibata, A., & Fukuda, K. (1994). Risk factors of fatality in motor vehicle traffic accidents. *Accident Analysis & Prevention, 26*(3), 391-397.

Shimamura, M., Yamazaki, M., & Fujita, G. (2005). Method to evaluate the effect of safety belt use by rear seat passengers on the injury severity of front seat occupants. *Accident Analysis & Prevention, 37*(1), 5-17.

Sicking, D. L., Albuquerque, F. D., Lechtenberg, K. A., & Stolle, C. S. (2009). Guidelines for implementation of cable median barrier. *Transportation Research Record: Journal of the Transportation Research Board, 2120*, 82–90.

Smith, K. M., & Cummings, P. (2004). Passenger seating position and the risk of passenger death or injury in traffic crashes. *Accident Analysis & Prevention, 36*(2), 257-260.

Srinivasan, K. (2002). Injury severity analysis with variable and correlated thresholds: ordered mixed logit formulation. *Transportation Research Record, 1784*, 132-142.

Tarko, A. P., & Azam, M. S. (2011). Pedestrian injury analysis with consideration of the selectivity bias in linked police-hospital data. *Accident Analysis and Prevention, 43*(5), 1689-1695.

Tarko, A. P., Bar-Gera, H., Thomaz, J., & Issariyanukula, A. (2010). Model-based application of abbreviated injury scale to police-reported crash injuries. *Transportation Research Record: Journal of the Transportation Research Board, 2148*, 59-68.

Tarko, A. P., Villwock, N. M., & Blond, N. (2008). Effect of median design on rural freeway safety: Flush medians with concrete barriers. *Transportation Research Record: Journal of the Transportation Research Board, 2060,* 29-37.

Ulfarsson, G., & Mannering, F. (2004). Differences in male and female injury severities in sport-utility vehicle, minivan, pickup and passenger car accidents. *Accident Analysis and Prevention, 36*(2), 135-147.

Villwock, N. M., Blond, N., & Tarko, A. P. (2011). Cable barriers and traffic safety on rural interstates. *Journal of Transportation Engineering, 137*(4), 248-259.

Washington, S. P., Karlaftis, M. G., & Mannering, F. L. (2011). *Statistical and Econometric Methods for Transportation Data Analysis (Second Edition).* Chapman and Hall/CRC.

Xiong, Y., & Mannering, F. (2013). The heterogeneous effects of guardian supervision on adolescent driver-injury severities: A finite-mixture random-parameters approach. *Transportation Research Part B, 49,* 39-54.

Xiong, Y., Tobias, J. L., & Mannering, F. L. (2014). The analysis of vehicle crash injury-severity data: A Markov switching approach with road-segment heterogeneity. *Transportation Research Part B, 67,* 109-128.

Yamamoto, T., & Shankar, V. N. (2004). Bivariate ordered-response probit model of driver's and passenger's injury severities in collisions with fixed objects. *Accident Analysis and Prevention, 36*(5), 869-876.

Zhu, X., & Srinivasan, S. (2011). Modeling occupant-level injury severity: An application to large-truck crashes. *Accident Analysis and Prevention*, *43*, 1427-1437.

Zou, Y., Geedipally, S. R., & Lord, D. (2013). Evaluating the double Poisson generalized linear model. *Accident Analysis & Prevention*, *59*, 497-505.

Zou, Y., Tarko, A. P., Chen, E., & Romero, M. A. (2014). Effectiveness of cable barriers, guardrails, and concrete barrier walls in reducing the risk of injury. *Accident Analysis & Prevention*, *72*, 55-65.

Appendix A Manual for Segment Selection in Google Earth

1. Job Objectives

1) Obtain homogeneous roadway segments with and without concrete barrier wall/guardrail/cable road barriers
2) Obtain qualitative and quantitative information on the relevant roadway and roadside features.

Q1: What is homogeneous roadway segment?

A: The homogeneous roadway segment designates a roadway segment where the roadway and roadside characteristics remain the same over the entire length of the segment under given traffic and weather conditions.

Q2: Why is there a need to obtain homogeneous roadway segments?

A: The ROR crashes are potentially influenced by roadway and roadside features. To further understand which of those features actually influence the ROR crashes and by how much, it is necessary to obtain the roadway segments with different roadway and roadside features and then conduct comparison on their crash counts among different segments.

Q3: What are the important characteristics of homogeneous roadway segment?

A: Worthy of note is that within each segment, the roadway and roadside features should be consistent. Although some of those interested features may not be exactly constant over the segment (e.g. the position of trees), they can be deemed as "homogenous" to a reasonable and acceptable level in some cases and that is where engineering judgment comes into play.

Q4: Why roadside hazard ratings need to be assessed?

A: The roadside hazard rating (0-7 scale) will be also used to assist the judgment. The information for roadside rating hazard is presented in the following sections. For a homogeneous segment, the difference between the maximum rating and minimum rating for one direction should be no larger than 2. The job listed here is to select those "homogenous" roadway segments and record information using the Google Earth software for our further analysis.

2. Job Description

The required job is divided into the following tasks:

1) Use the software Google Earth to select homogeneous segments which are close to the assigned spot. The segment selection and the homogeneity check are achieved by visual inspection on the Google Earth images of the roadway and roadside features.
2) Collect information for interested roadway and roadside features of the selected segments in Google Earth. Information for both traffic directions is required. Carefully fill in the data entry form available in a Excel spreadsheet.
3) Check the data input errors and make sure the standard for judging the segment homogeneity hold constant and reasonable over selected segments.

3. Work Procedure

Each student is assigned to a certain type of barrier and several sets of spots in Google Earth. Whatever the assigned type of barrier is, two types of spots are assigned in Google Earth and they are classified by the presence of a physical mile post. A “milepost spot” (yellow pin in Google Earth) designates a spot which is located exactly or very closely where a physical integer milepost is placed, whereas a “boundary spot” (red rectangle in Google Earth) designates a spot which is located around 0.5 miles away from the physical mile post. Data collectors should start their segment selection by zooming into a milepost spot. For each milepost spot, its closest two boundary spots define the boundary within which the finally selected segment should fall. The finally selected segment should only contain the milepost spot.

For data collectors assigned to collect information for the guardrail barriers, they also have to select a homogenous segment without any barrier as the “control group” right after they finish a guardrail segment selection. For the control group segment selection, instead of starting from the assigned milepost spot, data collectors should select the corresponding milepost spot by their own judgment based on the nearby roadway and roadside information. The selected control group segments should have similar roadway and roadside characteristics as their corresponding guardrail segments except for the presence of barrier.

Below is a detailed procedure for selecting homogenous segments.

i. **Check the presence of barriers.** In Google Earth, zoom into the assigned milepost spot and start to work under the “street view”. Check if there is a required type of barrier (barrier wall/guardrail/cable/non-barrier) around the spot.

If so, continue to the next step. If not, fill in the data entry form and add a note such as “no guardrail found”. Then move on to the next assigned milepost spot.

ii. **Set the “Reference Direction”.** Under the “street view”, there is at least one solid yellow line that shows the approximate path followed by the camera car. If there are two solid yellow lines, pick one of those. The direction in which the camera car was driving along the selected yellow line is the “reference direction”. Then the other direction is the “opposite direction”. It should be noted that those two directions are determined and recorded based on the **entire route direction**. For the most part, the interstates, U.S. highway, state and county routes follow the pattern of odd numbers corresponding to north-south routes and even numbers corresponding to east-west routes. So whichever the local direction may be, the finally recorded direction should be interpreted under the larger context of the entire route and could be only one of the following: E/W/N/S or CW/CCW (for beltways or loops such as I465, I469, etc.). Furthermore, the reference direction should be also interpreted in terms of whether it is in milepost increasing direction or milepost decreasing direction.

iii. **Check the consistency in roadway geometry and roadside hazard for both directions.** Move upward along the “reference direction” and watch the roadway features **for both directions** by slowly rotating the scroll wheel of the mouse under “street view” and then glancing from the “satellite view”. Keep moving upward until any one of the following situations occur:

- Beginning/end of a primary barrier (barrier wall/guardrail/cable)
  Note: when we select the segments for a required type of barriers, this type of barriers is of primary interest and defined as “primary barriers”, and then the other two types of barriers are the “secondary barriers”.
- Beginning/end of a horizontal curve
- Beginning/end of a rumble strip

- Presence of a boundary spot
- Presence of an intersection or interchange
- Presence of a major road construction area
- Presence of a bridge
- Change of the number of lanes
- Change of the lane width
- Change of the median width
- Change of the shoulder width
- Other abrupt changes on roadside characteristics such as:
    - Secondary barriers
    - Embankments
    - Curbs
    - Culverts
    - Ditches
    - Density and distance from the edge of travelled lanes to trees
    - Other rigid and fixed objects such as utility poles, buildings, retaining walls, cliffs, noise barriers etc.

iv. **Record the downstream endpoint of the homogeneous segment.** Once stop moving because any of those aforementioned consistencies is violated, record the longitude and latitude of a point around 50 feet (use 500 feet only when the changed feature is the presence of intersections) ahead of where stop moving occurs as “end latitude” and “end longitude”. This point is the downstream endpoint of the homogeneous segment.

v. **Record the upstream endpoint of the homogenous segment.** Go back to the assigned milepost point and move backward toward the upstream of the solid yellow line until the consistency of any roadway and roadside characteristics is violated or a boundary point is reached. The point around 50 feet (use 500 feet only when the changed feature is the presence of an intersection) ahead of where stop occurs is the upstream endpoint of the homogeneous segment. Record the longitude and latitude of this point as “start latitude” and “start longitude” respectively. From now on, we have finished selecting one homogenous segment.

vi. **Check the location of the assigned spot in the selected segment.** The selected segment should contain the milepost spot and fall into the region between the two boundary spots. If so, go to the next step. If not, record the milepost spot ID, “start latitude”, “start longitude”, “end latitude”, and “end longitude”, add a note such as “spot not contained in the segment” or “segment exceeds boundaries”, and then move on to the next assigned milepost spot.

vii. **Check the temporal consistency of roadway and roadside characteristics.** Use the “time slider” in Google Earth to determine if the roadway and roadside characteristics on the selected segment have experienced significant changes over the years. If so, record the most recent year that those changes could be seen in Google Earth.

viii. **Measure and collect information in Google Earth “Satellite view”.** Use the “show ruler” tool provided in “satellite view” to help measure the distance of certain features. The items required to measure or record are as listed as the following:

- Observers’ Information
  - Observer Name
  - Computer No. (1/2/3/4/5)
  - Work Date (e.g., May-6)
  - Work Start Time (e.g., 14:00)
  - Work End Time (e.g., 4:30)
- Assigned Barrier Type (Barrier Wall/Guardrail/Cable/Non-Barrier)
- Assigned Milepost Spot

    - Spot ID (e.g., BW14_I 465_14)
    - Route Name (e.g., I 65)
    - Milepost (e.g., 26)
    - Latitude (e.g., 30°37'40.72"N)
    - Longitude (e.g., 96°20'3.87"W)
- Reference Direction
    - E/W/N/S or CW/CCW
    - Milepost Increasing (1-yes; 0-no)
- Segments' Information
    - Start Latitude (i.e. latitude of the upstream endpoint in the reference direction)
    - Start Longitude (i.e. longitude of the upstream endpoint in the reference direction)
    - End Latitude (i.e. latitude of the downstream endpoint in the reference direction)
    - End Longitude (i.e. longitude of the downstream endpoint in the reference direction)
    - Segment Length
- Primary Barriers
    - Primary Barrier Type (Concrete/Guardrail/Cable)
    - Reference Direction
        - Left Offset
        - Right Offset
    - Opposite Direction
        - Left Offset
        - Right Offset
- Secondary Barriers
    - Secondary Barrier Type (Concrete/Guardrail/Cable)
    - Reference Direction
        - Left Offset

        - Right Offset
    - Opposite Direction
        - Left Offset
        - Right Offset
- Roadway Geometry
    - Shoulder Width
        - Reference Direction
            - Left Shoulder Width
            - Right Shoulder Width
        - Opposite Direction
            - Left Shoulder Width
            - Right Shoulder Width
    - Median
        - Median Width
        - Median Traversable (1-Yes; 0-No)
    - No. of Lanes
        - Reference Direction
        - Opposite Direction
    - Presence of Horizontal Curves (1-Yes; 0-No)
- Roadside Features (for both reference direction and opposite direction)
    - Non-traversable objects
        - Type (1-Trees; 2-utility poles; 3-buildings; 4-culverts; 5-ditches; 6-retaining walls; 7-cliff; 8-noise barrier; 9-luminare supports; 10-others)
        - Continuity: (1-Continuous; 0-Intermittent)
        - Offset from Edge of Traveled Way
        - Density of Non-traversable objects (or the gap length)
    - No. of Driveways
        - Reference Direction
        - Opposite Direction

    - Embankment
        - Embankment Slope (Steep/Medium/Flat)
        - Embankment Width (Wide/Medium/Narrow)
    - Road Hazard Rating (1-7)
        - With barrier
        - Without barrier
- Presence of Ramble Strips (1-Yes; 0-No)
    - Reference Direction
        - Left Side
        - Right Side
    - Opposite Direction
        - Left Side
        - Right Side
- Image Data
    - Satellite View Date (e.g., 12/2007)
    - Street View Date (e.g., 08/2011)

ix. **Check the possible typos and errors** for the entered information. For students with guardrail barriers, continue to the next step to select a matched non-barrier segment. For other students, move onto the next assigned milepost spot for barriers, and repeat the steps i to ix until the required number of segments have been selected. Make sure the standard for judging the segment homogeneity hold constant and reasonable over selected segments.

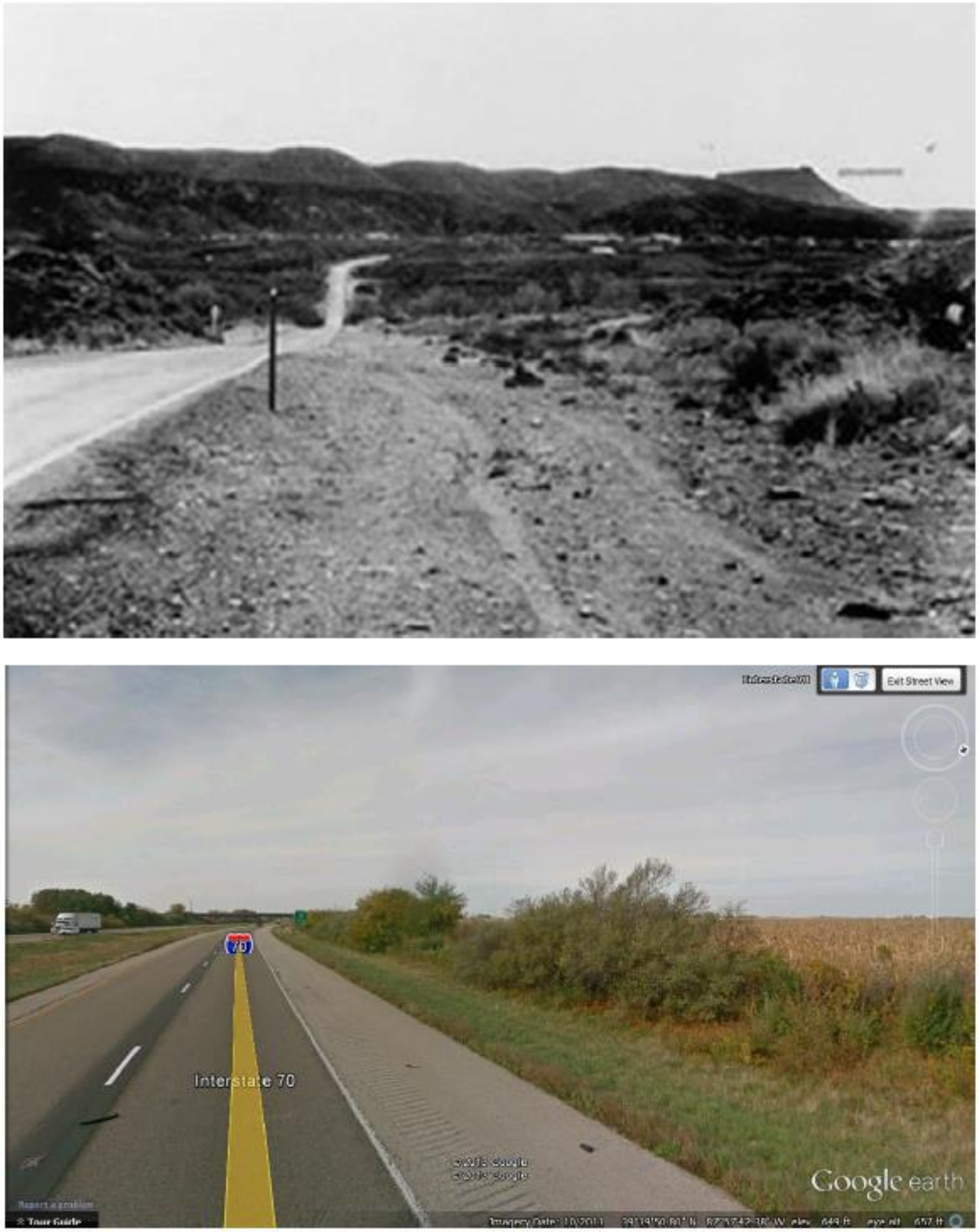
(NOTE: THE FOLLOWING STEP IS ONLY FOR STUDENTS WITH GUARDRAIL BARRIERS TO GO THROUGH)

x. **Select the homogeneous segment for non-barrier segment**. The objective of this step is to select a non-barrier homogenous segment paired with its corresponding barrier segment, which has been selected and recorded by the previous steps. Use the measure tool to help search for a spot 1 mile away from the assigned milepost for guardrail segment selection. Zoom into the spot and check the barrier presence. If no barrier is present, then this spot is the milepost spot for the non-barrier homogeneous segment and repeat step iii to ix to finish the segment selection and recording procedure, and finally move on to another assigned milepost spot for selecting a new set of barrier and non-barrier segments. If there is any barrier in this 1-mile away spot, then increase the searching distance by another 1 mile and check the barrier presence. Repeat the above procedure until a milepost spot without any barrier is found.

4. Pictures for Roadside Hazard Rating

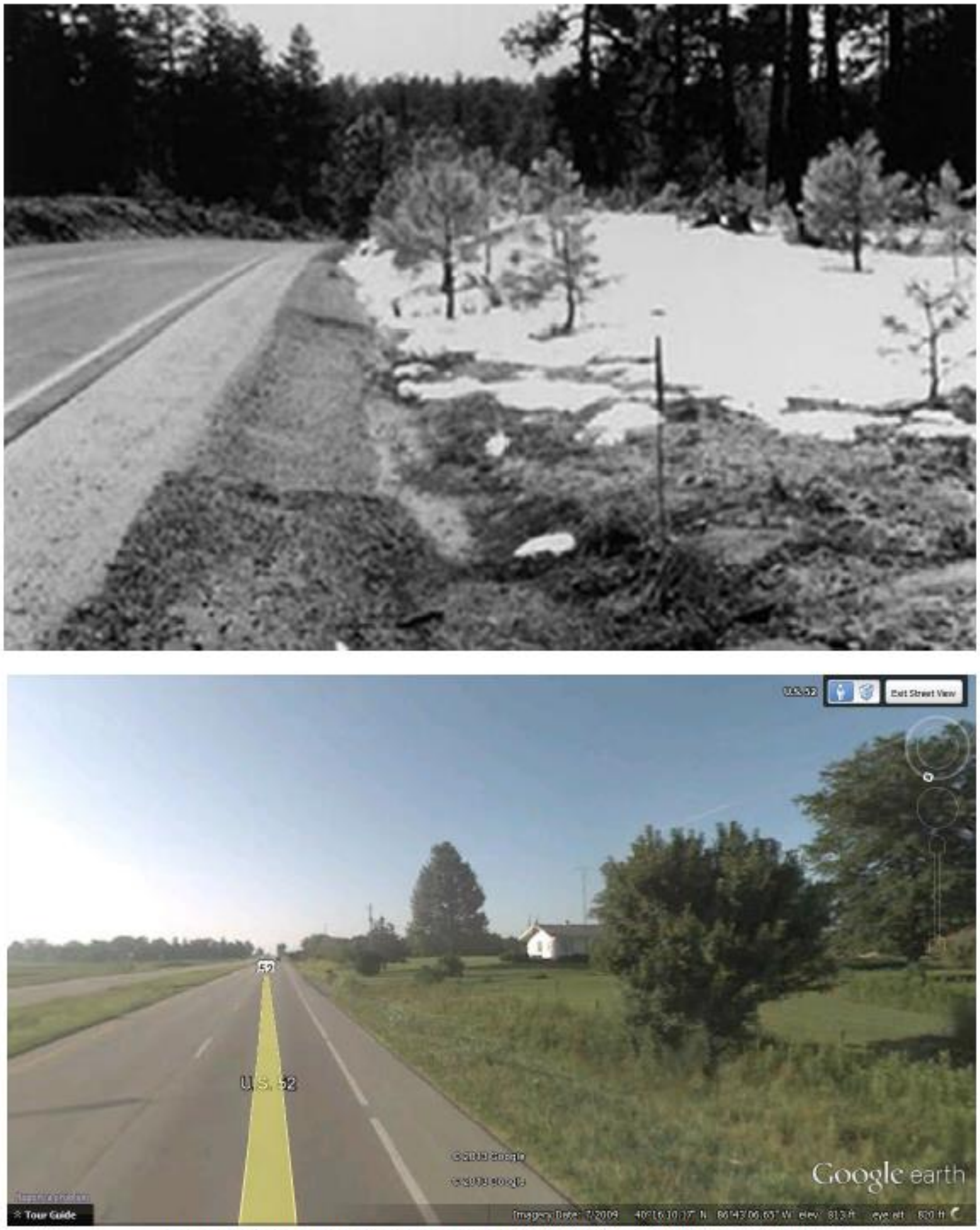
Clear zone greater than or equal to 30 ft; sideslope flatter than 1V:4H, recoverable.

Figure A-1 Typical Roadway with Roadside Hazard Rating of 1 (Highway Safety Manual, 2010)
(Top: Original Picture; Bottom: Reproduced Picture in Google Earth)



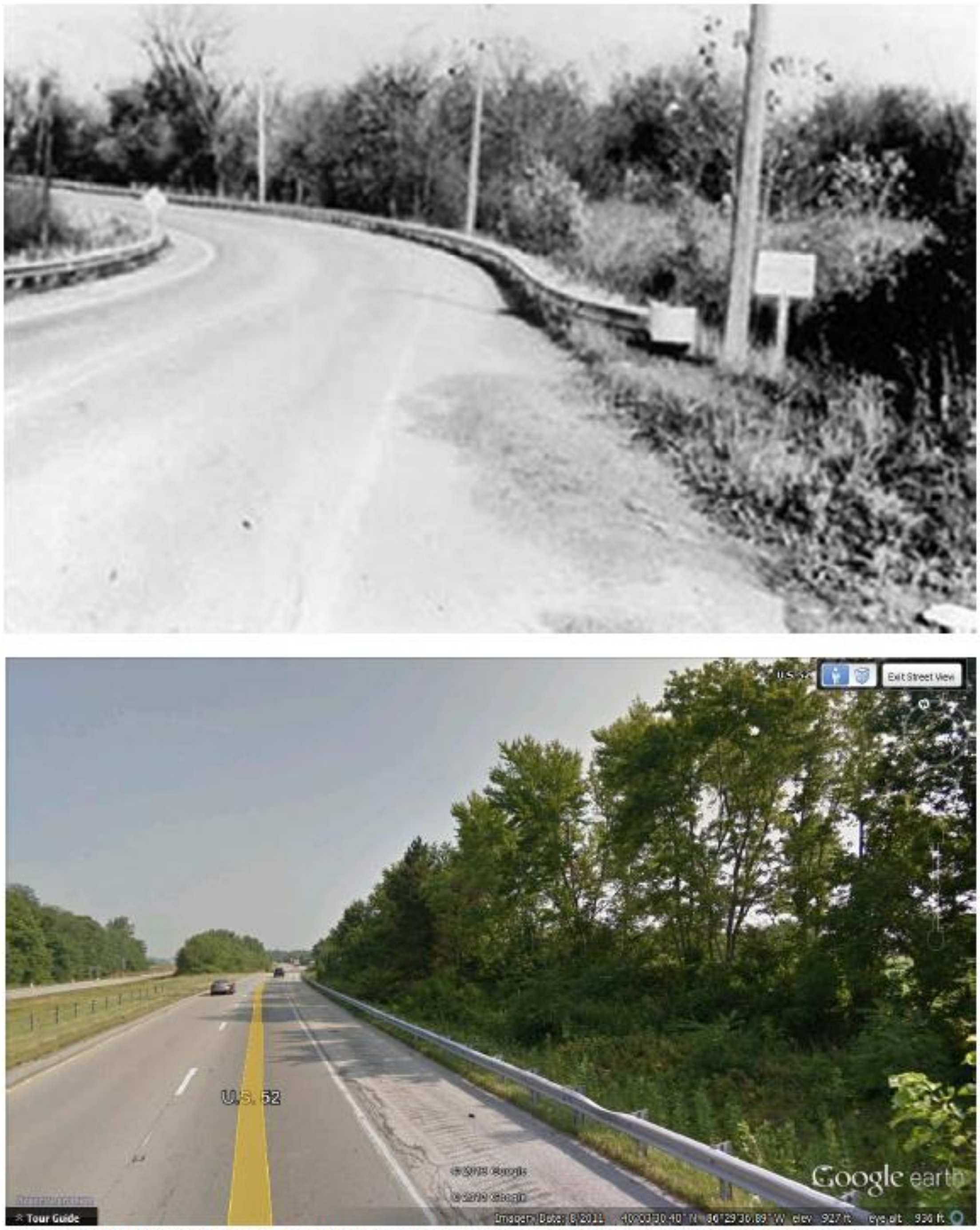
Clear zone between 20 and 25 ft; sideslope about 1V:4H, recoverable.

Figure A-2 Typical Roadway with Roadside Hazard Rating of 2 (Highway Safety Manual, 2010)
(Top: Original Picture; Bottom: Reproduced Picture in Google Earth)



Clear zone about 10 ft; sideslope about 1V:3H, marginally recoverable.

Figure A-3 Typical Roadway with Roadside Hazard Rating of 3 (Highway Safety Manual, 2010)
(Top: Original Picture; Bottom: Reproduced Picture in Google Earth)

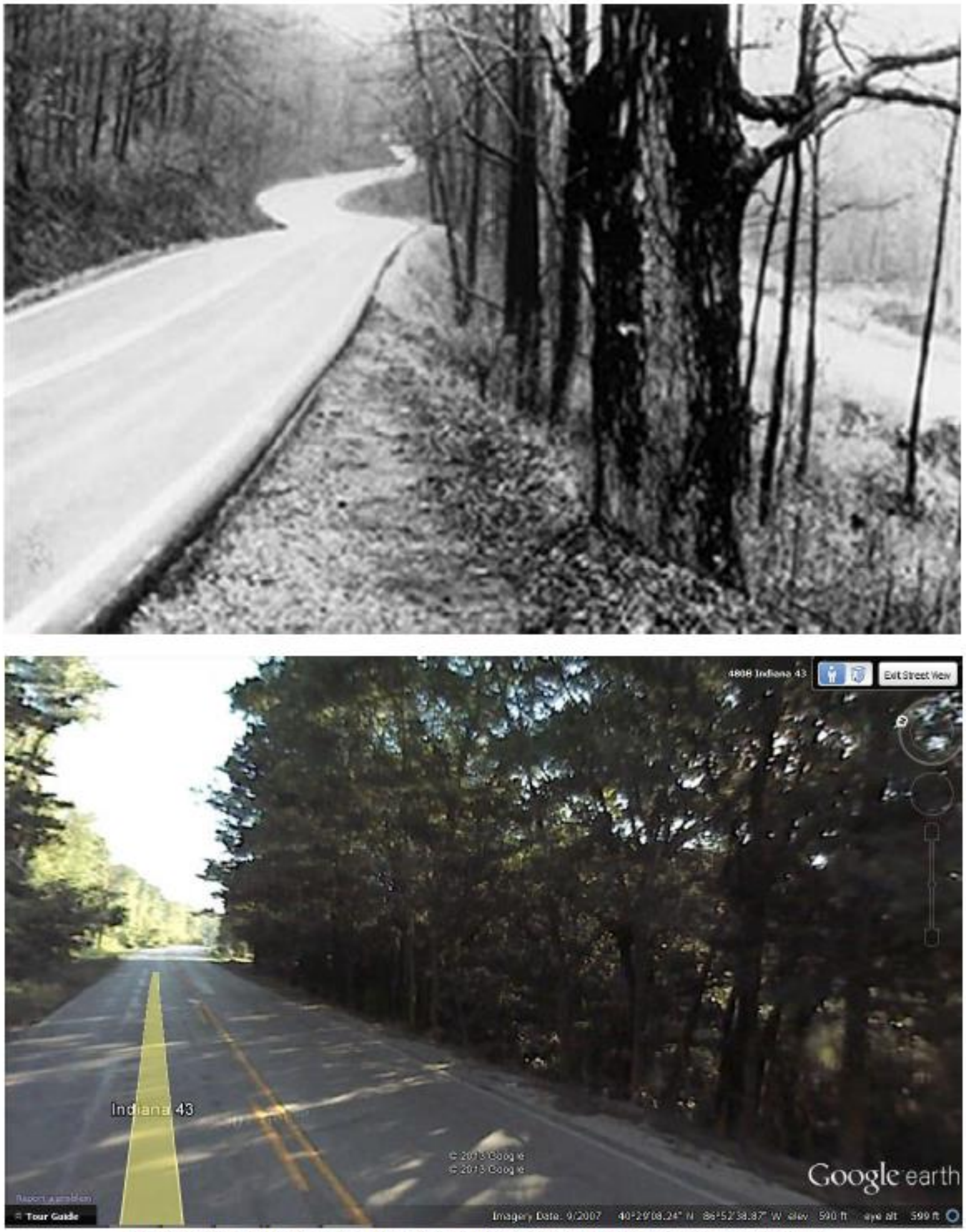


Clear zone between 5 and 10 ft; sideslope about 1V:3H or 1V:4H, marginally forgiving, increased chance of reportable roadside crash.

Figure A-4 Typical Roadway with Roadside Hazard Rating of 4 (Highway Safety Manual, 2010)
(Top: Original Picture; Bottom: Reproduced Picture in Google Earth)

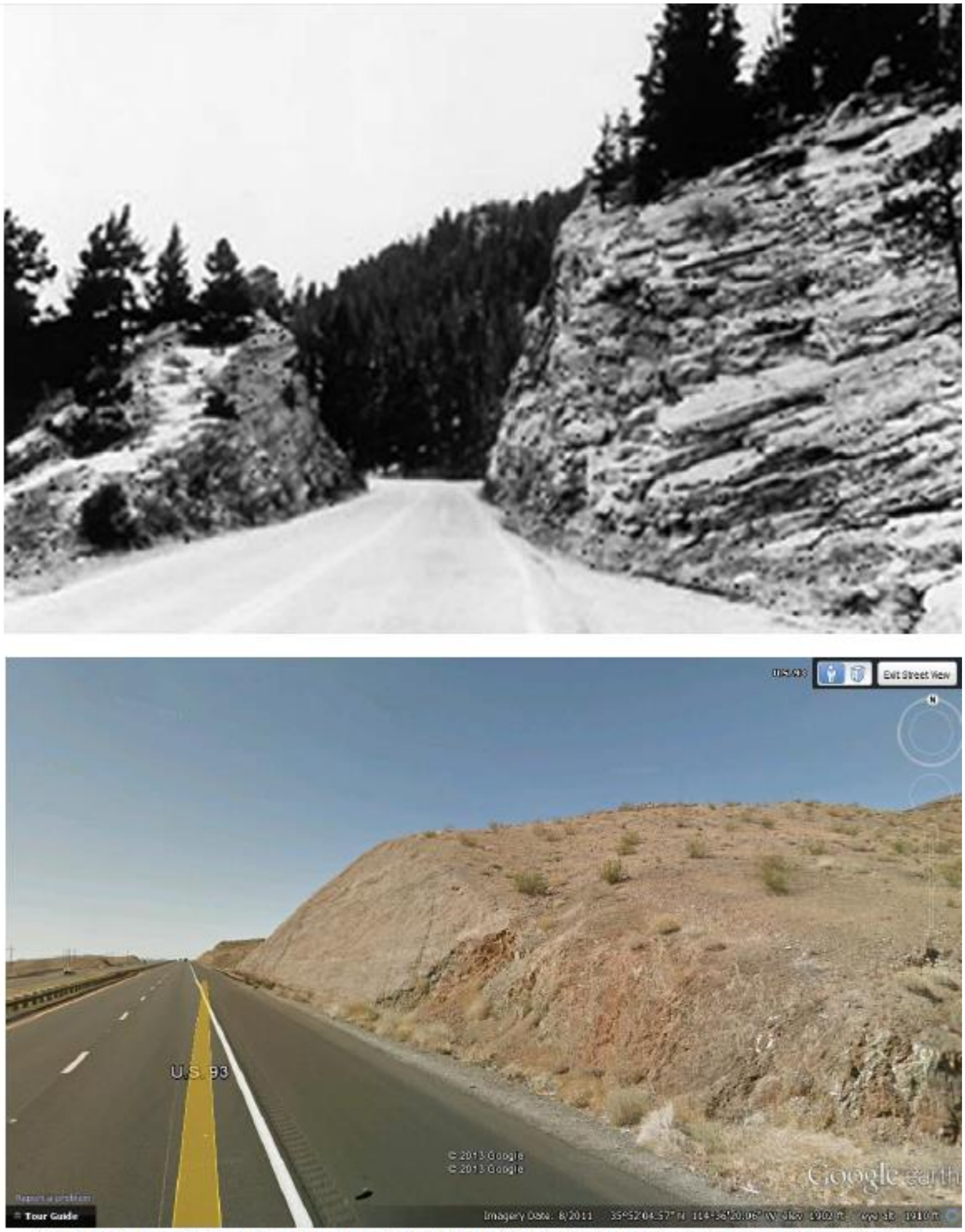
Clear zone between 5 and 10 ft; sideslope about 1V:3H, virtually non-recoverable.

Figure A-5 Typical Roadway with Roadside Hazard Rating of 5 (Highway Safety Manual, 2010)
(Top: Original Picture; Bottom: Reproduced Picture in Google Earth)



Clear zone less than or equal to 5 ft; sideslope about 1V:2H, non-recoverable.

Figure A-6 Typical Roadway with Roadside Hazard Rating of 6 (Highway Safety Manual, 2010)
(Top: Original Picture; Bottom: Reproduced Picture in Google Earth)



Clear zone less than or equal to 5 ft; sideslope about 1V:2H or steeper, non-recoverable with high likelihood of severe injuries from roadside crash.

Figure A-7 Typical Roadway with Roadside Hazard Rating of 7 (Highway Safety Manual, 2010)
(Top: Original Picture; Bottom: Reproduced Picture in Google Earth)

Appendix B Variables Extracted from Crash Report

No.Lanes: the number of lanes in the vehicle travelling direction

Curve: the indicator variable for the presence of a horizontal curve.

1- A horizontal curve is present

0- A horizontal curve is not present

Intersection: the indicator variable for the presence of any type of road junctions such as a four-way intersection, a T-intersection, a roundabout, and a ramp.

1- An intersection is present

0- An intersection is not present

BarrierMS: the collided barrier is in the median or along the roadside.

M - The collided barrier is in the median

S – The collided barrier is along the roadside

BarrierLR: the **collided** barrier is on the left or right to the vehicle.

L – The collided barrier is on the vehicle's left

R – The collided barrier is on the vehicle's right

BarrierType: the type of the collided barrier.

BW – Barrier wall

CB – Cable barrier

G – Guardrail

VehROR: the indicator variable for whether or not the vehicle leaves the roadway at some point.

1 – The vehicle leaves the roadway

0 – The vehicle does not leave the roadway

EventBefore: the coded event that the vehicle is involved in BEFORE it leaves the roadway. See the event codes that followed.

VehLR1: the vehicle goes to the left or right side (relative to its travelling roadway) after it leaves the roadway.

L – The vehicle goes to the left side relative to its travelling roadway

R – The vehicle goes to the right side relative to its travelling roadway

VehCM1: the vehicle crosses the median and gets on the roadway in the opposite direction

1 – The vehicle crosses the median

0 – The vehicle does not cross the median

ROREvent1: the event category the vehicle is involved in after it leaves the roadway.

1 – Hit a roadside barrier

2 – Hit a fixed roadside object

3 – Hit a moving roadside object (pedestrian, bicycle, another vehicle, etc.)

4 – Roll over and does not hit anything

5 – Does not roll over or hit anything on the roadside

6 – Other, please specify

EventCode1: the coded event that the vehicle is involved in AFTER it leaves the roadway. If there are multiple events involved, use blank space to separate those event codes. See the event codes that followed.

State1: the state of the vehicle after its run-off-road event.

a – Come to a rest on the roadside or in the median in its travelling direction

a1 – Com to a rest on the OPPOSITE roadside

a2 – Come to a rest on the OPPOSITE roadway

b – Penetrate or roll over the collided object

c – Redirect back to the roadway and hit an another vehicle

d – Redirect back to the roadway and does not hit anything

e – Other, please specify

VehLR2, VehCM2, ROREvent2, EventCode2 and **State2** are required to be filled out only when the vehicle leaves the roadway again after it returns to roadway from the last run-off-road event.

Entries for Event Coding:

01 - Another Motor Vehicle

02 - Pedestrian

03 - Bicycle

04 - Railway Vehicle/Train/Engine

05 - Deer

06 - Animal Other Than Deer

07 - Animal Drawn Vehicle

15 - Overturn/Rollover

16 - Fire/Explosion

17 - Immersion

18 - Jackknife

19 - Cargo/Equipment Shift Or Loss

20 - Off Roadway

21 - Fell From Vehicle (Non Collision)

30 - Impact Attenuator/Crash Cushion

31 - Bridge Overhead Structure

32 - Bridge Pier Or Abutment

33 - Bridge Parapet End

34 - Bridge Rail

35 - Guardrail Face

36 - Guardrail End

38 - Highway Traffic Sign Post

39 - Overhead Sign Post

40 - Light/Luminaire Support

41 - Utility Pole

42 - Other Post/Pole Or Support

43 - Wall/Building/Tunnel

44 - Work Zone Maintenance Equipment

45 - Embankment

46 - Curb

47 - Ditch

48 - Culvert

49 - Fence

50 - Mailbox

51 - Tree

52 - Other - Explain In Narrative

54 - Equipment/Mechanical Failure

55 - Downhill Runaway

56 - Separation Of Units

57 - Thrown Or Falling Object

58 - Parked Motor Vehicle

60 - Cable Barrier

61 - Concrete Traffic Barrier

VITA

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